Survey of
Modern Electronics

SURVEY OF MODERN ELECTRONICS
by Paul G. Andres

BASIC MATHEMATICS FOR ENGINEERS
by Paul G. Andres, Hugh J. Miser,
and Haim Reingold

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Dedicated to the young
engineers of today
whose work will make a better
world of tomorrow

Preface

This book is intended to be a textbook for a short course in electronics. It is based on lecture and classroom notes from a condensed one-semester and a detailed two-semester course given to mechanical, chemical, and industrial engineering students to familiarize them with the basic principles of construction, operation, and application of electron tubes. It demonstrates the vital importance of electronics in nearly all branches of science and engineering.

It is assumed that the student has a knowledge of elementary electrical engineering; however, in the author's teaching experience, students who had completed courses in physics and d-c fundamentals and who were concurrently taking a course in a-c fundamentals had little difficulty with the subject. In making a representative survey of electronics the emphasis, of necessity, has been placed on a descriptive, rather than on a mathematical, treatment. Depending on the time available for the course and on the previous training of the students, the more elementary material, or the more elaborate electron-tube applications, may be omitted or curtailed without loss of continuity.

The following features of the book assist in achieving its designed purpose:

1. The required electrical engineering fundamentals are reviewed in many cases before discussing the electronic devices and circuits on which they are based. This approach fixes these principles more firmly in the student's mind so that they will be of practical aid to him in the future.

2. The description of nearly every tube is followed immediately by one or more practical applications. Many of these give detailed numerical data; they help the student to obtain more definite concepts of the equipment.

3. Specific applications are selected to arouse and maintain reader interest and indicate some of the capabilities of electronics.

4. Numerous halftones are provided to give the student a

general idea of the physical size, shape, and utilization of electronic equipment.

5. The final chapters review salient applications of electronics in instrumentation, communication, control, and heating. They offer practice in the reading of circuit diagrams.

6. Frequently circuits are encountered that show interconnection of tube electrodes; for example, a triode may be connected and used as a diode. Tubes are sometimes connected in this fashion in order to obtain desirable characteristics. The student should be acquainted with this practice.

7. General references in the appendix, and specific references and problems located at the end of each chapter, are included to provide opportunity for additional study.

It is hoped that this book may supply the textual need for a short survey course in electronics for electrical engineering students before they specialize in power, communication, or any other field. Such a course offers the beginner the assurance that he has the aptitude, ability, and interest to make some form of electronics his life's work, or the equal advantage of indicating, in a very short time, that his talents will bring greater satisfaction in some other field of electrical engineering.

Since education is a lifelong process, the book should afford an opportunity, outside the classroom, for engineers and technical men who come in contact with electronic equipment to acquaint themselves with the basic principles of the subject.

The author wishes to express his appreciation to the engineers, government agencies, and companies who supplied technical data and photographs, as well as to the many engineers and authors whose work formed background material. He is particularly grateful to members of the staffs of the Allis-Chalmers Manufacturing Company, General Electric Company, Radio Corporation of America, Western Electric Company, and Westinghouse Electric Corporation for their generous help and unstinting efforts to supply data and material. The author also acknowledges his deep indebtedness to Prof. L. T. Anderson of the University of Minnesota for a critical reading of the manuscript and suggestions for its improvement, and to Dr. J. E. Hobson, Executive Director of Stanford Research Institute, for his interest and encouragement in the writing of this book.

PAUL G. ANDRES

Riverside, California
July, 1950

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Basic Concepts and Current Conduction

Electricity for power and light in home and industry has been used at a rapidly increasing rate since the start of the century. One needs only to think of the many power plants and the loads they supply to realize that we live in an electrical age. There is an installed generating capacity of over 70,000,000 horsepower in the United States. These plants make light and power available to more than 100,000,000 people in their homes and to nearly 5,000,000 industrial plants and commercial establishments.

Mass production in our modern industrial world demands analysis and scrutiny of every operation to obtain the most economical manufacturing cost and to insure a uniform product. Electricity plays an important role in industrial plants. Electrical energy is clean; aside from heat there are no waste by-products such as would be obtained if steam, gas, or oil engines were used to drive production machines. An even greater advantage lies in its flexibility and ease of control. Conductors carry electrical energy silently and with minimum loss either overhead or underground from a central station to the motor-driven machines, welders, or electric furnaces. A simple mechanism permits an operator to increase or decrease the speed or power requirement of each machine without disturbing that of any other machine.

A modern machine shop is shown in Fig. 1–1. The plant is air-conditioned; all incoming air is heated or cooled, humidified or dehumidified, as required, and filtered through self-cleaning, electric precipitation-type filters. Because of low building losses,

cooling is required for the shop under normal load conditions for outside temperatures as low as —45° F.

Manufacturing, the science and art of fabricating things, has always been faced with the difficulties of producing to engineering specifications. The constant improvement of a product is an essential requirement for survival in the competitive market of



FIG. 1–1. Modern machine shop uses individual, motor-driven machines. Fluorescent lamps and loud-speakers are set in acoustic ceiling. *Courtesy Woodward Governor Company.*

our free enterprise system. Finesse and speed of production, in large measure, depend on control, and consequently if this is made more precise greater uniformity of product is achieved.

One of the features of electronics is the utilization of devices that control the magnitude of an electric current in extremely small gradations or that open and close an electric circuit with precise timing by direct action on the electric charges without moving the mass of an ordinary conductor. Mechanical switches and contactors are commonly used to open and close electric circuits, but none have as yet been developed that can make and break a 10,000-ampere circuit 5 times a second; electronic contactors, however, can do this job easily, silently, efficiently, and dependably. But electronics is applied not only to industrial

control; it is the foundation for radio, television, long-distance telephony, radar, and other navigational aids. It finds extensive application in the fields of power conversion, illumination, heating, and measurements.

1–1. Electrons, Ions, and Radiation

Mankind has always been interested in the nature and constitution of matter, but only recently—during the last two centuries—have we made much progress in ascertaining its true nature.

Matter is composed of a number of *molecules*, the smallest physical parts of a substance; and molecules, in turn, consist of suitably combined *atoms*, the building stones of our world. Atoms, as found in nature, may be any one of more than 90 different types or *elements*.

Crookes, who discovered the element thallium in 1879, indicated that an individual, electrically charged particle existed in his vacuum and gaseous tube experiments. Later Wilson, Fleming, Richardson, Millikan, and others isolated this basic electric charge and measured it. In 1913 Niels Bohr, a Danish physicist, devised a theory that provides us with a working model of atomic structure.

Bohr's theory states that the atom consists of a dense nucleus of positive charges, termed *protons*, around which discrete, indivisible negative charges or *electrons* move in definite orbits. The number of protons varies according to the *atomic number* of the element. Hydrogen, the lightest element, has 1; copper has 29; and curium, the heaviest element discovered so far, has 96 centrally located protons. Orbits of electrons external to the nucleus are arranged in the form of shells as shown simplified in Fig. 1–2. A complex atom such as copper has four successive shells which contain 2, 8, 18, and a single electron, a total of 29 electrons. Each electron has a mass of 9.11×10^{-31} kilogram and an electrical charge of 1.60×10^{-19} coulomb. It has an equivalent diameter of about 10^{-15} meter. The diameter of the outermost orbit of electrons in an atom is of the order of 10^{-10} meter; the central, positively charged nucleus has a diameter of about 10^{-14} meter.

The dense, positively charged nucleus contains most of the mass of the atom, since each proton is approximately 1840 times as heavy as an electron. The total positive charge in the nucleus

is always an integer multiple of the charge of an electron although, of course, opposite in sign. In a normal atom the number of protons is the same as the number of orbital electrons. In 1932 it was discovered that neutral particles or *neutrons* exist in the nuclei of helium and heavier atoms. The neutron has no elec-

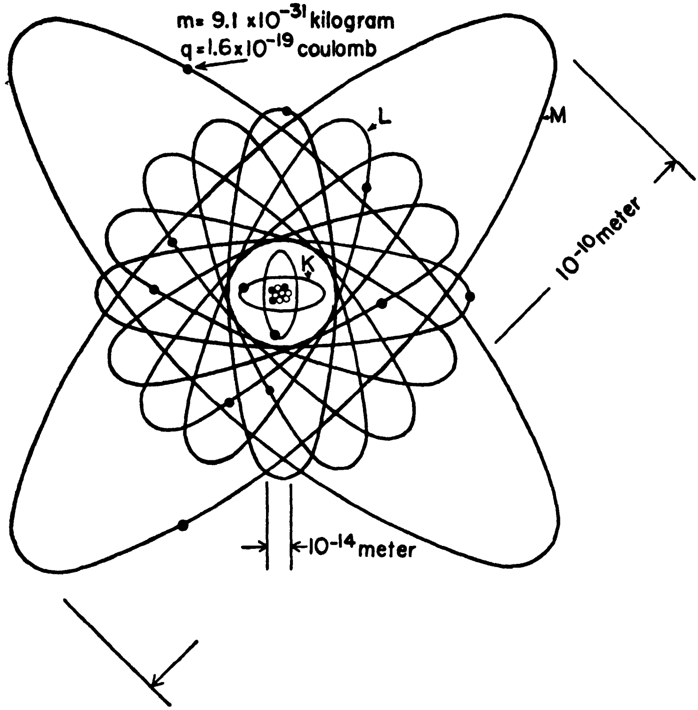


FIG. 1–2. Simplified representation of a magnesium atom.

trical charge, but it has almost exactly the same mass as the proton. The mass number of an atom is determined by the number of neutrons plus the number of protons. Many elements are made up of mixtures of atoms which contain the same number of protons but in which the number of neutrons differ. The components, called *isotopes*, are chemically identical even though the number of neutrons is not the same. Frequently an element is designated by symbols, such as ${}_3Li^6$ or ${}_3Li^7$, where the subprefix, indicating the atomic number, is followed by the chemical symbol, and the superscript gives the mass number of the particular

isotope. Chemical tables give the atomic weight of lithium as 6.940, from which the proportion of each of the two isotopes may be deduced.

In 1932 J. D. Cockcroft and E. T. S. Walton developed a method of transforming hydrogen and lithium into helium with the simultaneous release of an extremely large amount of energy. This conversion may be written as follows:

$$_1H^3 + {_3Li^7} \longrightarrow 2{_2He^4} + \text{Energy.} \qquad (1\text{–}1)$$

The energy, which is millions of times greater than the energy released in ordinary chemical reactions for comparable weights, comes into existence because a tiny portion of the atomic mass is converted into energy. More recently it has been discovered that new and heavier chemical elements, previously unknown, can be produced by transmutation from uranium. Two of these are called neptunium and plutonium. Plutonium has a $_{94}Pu^{239}$ isotope, and it, as well as the $_{92}U^{235}$ isotope, is made unstable when a slow-moving neutron is added to its atomic structure. In either instance, the atom splits, divides, or fissures into several fragments with a tremendous liberation of light, heat, and mechanical energy caused by the conversion of a small portion of the original mass into energy. As a hypothetical case we may assume that a neutron is added to a $_{92}U^{235}$ isotope. This causes nuclear fission; the atom breaks up into two medium-sized atoms of barium and krypton, whose total masses are less than the original uranium mass, and neutrons are released together with an extraordinary amount of energy.

The first atomic bomb was detonated by the Atomic Commission of the United States government in New Mexico in 1945. As may be inferred from Fig. 1–3, where estimates indicate that only a fractional part of an ounce of matter was changed to energy, the sudden release of energy from an atom bomb is greater than any explosion so far produced by man. The subjugation of atomic power and its use for the welfare of mankind will probably prove to be more important than any other scientific contribution or discovery.

Only an extremely small portion of the space within the atom is occupied by the nucleus and the orbital electrons; the major portion consists of empty space. An electron may be shot or projected through a normal atom without causing disturbance,

provided it does not approach too closely to, or collide with, another electron during the passage. The outer orbital electrons



FIG. 1-3. Atom-bomb blast. Destroyed large portion of Nagasaki, Japan, 1945 *Courtesy United States Army Air Forces.*

of an atom enter into chemical reactions and are also the ones that are most easily disturbed or detached by a transient electron. The study of the behavior and utilization of these outermost

electrons of an atom is the major problem in electronics; nuclear physics will undoubtedly provide a fruitful field for a completely new endeavor in science and engineering.

Unlike electric charges attract each other and like charges repel. Coulomb discovered this fact many years ago and formulated the law named after him. It is commonly written in the form

$$f = \frac{Q_1 Q_2}{\epsilon d^2}, \tag{1-2}$$

where f is the force in newtons, Q_1 and Q_2 are the magnitudes of the charges in coulombs, ε is a constant which depends on the intervening space or material, and d is the distance in meters between the charges. The constant ε has a value of 1.11×10^{-10} for free space with the units chosen as above in m.k.s. units; it is approximately the same if the space between the charges is filled with air. Each charge is assumed to be concentrated at a point. It may be noted in passing that a coulomb consists of about 6.25×10^{18} electrons, an extremely large number of individual charges.

The electron and the proton consist of equal quantities of negative and positive charges. The electric fields of these charges balance each other so that a normal atom exhibits no external electrical field.

Let us now assume that an electron moves through space with a constant velocity and penetrates a neutral atom. If it approaches an orbital electron of that atom, the repulsive force between them, according to Coulomb's law, reaches large values. If the energy is sufficiently large, a portion of that energy is absorbed from the transient electron and this causes the orbital electron to move from an inner to the next outer orbit or shell, as shown diagrammatically at point a in Fig. 1–4.

Electron displacement produces an unstable condition of the atom known as *excitation;* the atom contains excess energy. The tendency is always to return to the normal state, and so, when the electron returns from the outer to the inner shell (point b in Fig. 1–4), the excess energy can manifest itself only as radiant energy. This energy is radiated at a frequency or group of frequencies along the electromagnetic spectrum in such form as X rays, ultraviolet radiation, or light. The energy required to

move an electron from the L shell to the M shell is greater than that required to move one from the M shell to the N shell, and higher radiation frequencies result when the electron that has moved from the L shell to the M shell returns to its normal orbit. Sufficient energy must be imparted to move electrons from the innermost or K shell to the L shell in order to produce very high frequencies. This requires high velocities on the part of the transient electrons, since it is the absorbed kinetic energy, $\frac{1}{2}mv^2$, which causes electrons to move from one shell to the next.

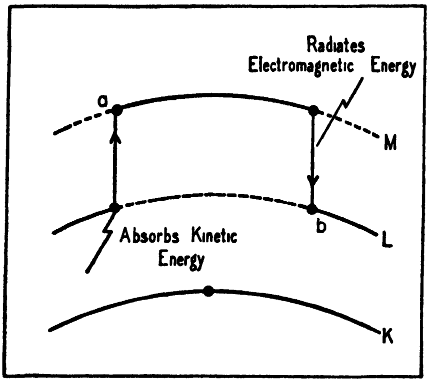


FIG. 1-4. Simplified diagram of atomic excitation.

Radiant energy, such as X rays, ultraviolet radiation, and light, also cause excitation of the surface atoms of certain substances. This property is used, for instance, in fluorescent lamps and in devices for detecting specific minerals that radiate light of a characteristic color when subjected to invisible ultraviolet radiation.

If the energy imparted by the transient electron, or if the impressed electromagnetic radiation, is sufficiently great, an electron within the bombarded atom leaves entirely instead of shifting from one energy level to the next. This process is known as *ionization*. The remainder of the atom manifests a positive charge, the equilibrium of electric charges in the atom having been destroyed by the removal of the electron. This remainder is termed a *positive ion*. The removed electron may attach itself to a neutral atom, causing it to exhibit a negative charge. Such an atom is a *negative ion*. Ions are encountered when an electric current flows through conducting solutions and when electricity is conducted through gases.

Electrical engineering concerns itself with the separation of electrical charges and their movement to perform useful work. In electronics and its applications these charges are caused to flow through vacuum or gaseous tubes, and control operations

are effected by operating directly on the individual electric charges.

1–2. Conduction through Metals

Copper and other metals, termed *conductors,* transmit electrons easily by passing them from one atom to the next since at least one electron in each atom is held rather loosely and the orbits of the outer electrons of two or more atoms overlap. Protons do not move; they are fixed in position. Electrical insulators, however, have very few free or roving electrons and the electrons are held more firmly to the atoms and molecules; such materials do not conduct charges easily.

When an electric charge of Q coulombs moves through a conductor in a time of T seconds, an electric *current* of I amperes flows, or

$$I = \frac{Q}{T}. \tag{1–3}$$

The rate of current flow is 1 ampere when 1 coulomb, that is, 6.25×10^{18} electrons, passes a given point in 1 second. The milliampere (0.001 ampere) and the microampere (0.000,001 ampere) are frequently encountered in electronic circuits.

When a current flows, the battery or generator that separates the charge of Q coulombs does work equivalent to W joules. The *electromotive force, difference of potential,* or *voltage* E is defined:

$$E = \frac{W}{Q}. \tag{1–4}$$

The unit of electromotive force is the volt, which is 1 joule per coulomb. Common power-line voltages are 110, 220, and 440 volts. The millivolt (0.001 volt) and the microvolt (0.000,001 volt) are terms used in low-voltage work; the kilovolt (1000 volts) is commonly used in high-tension applications.

Years ago Ohm formulated the basic law that the current I in a direct-current circuit varies directly with the voltage E and inversely with the resistance R, or

$$I = \frac{E}{R}. \tag{1–5}$$

Resistance may be defined as the ratio of voltage over current. It depends, in general, on the material, dimensions, and temperature of the conductor. The unit of resistance is the ohm. The microhm (0.000,001 ohm) and the megohm (1,000,000 ohms) are used in the designation of very low and very high resistances respectively. The reciprocal of resistance is conductance; its unit is the mho, and it is designated by the letter G.

Multiplying the expression for voltage by that of the current, we obtain

$$EI = \frac{W}{\not{Q}} \cdot \frac{\not{Q}}{T} = \frac{W}{T}. \tag{1-6}$$

It will be noted that this product is work per time, or *power*. The unit for power is the watt. The milliwatt (0.001 watt) and the microwatt (0.000,001 watt) are used to measure very small powers; the kilowatt (1000 watts) is generally used in the designation of commercial powers. By substituting the expressions for E and I from Ohm's law, the equation for power may be written

$$P = EI = I^2R = \frac{E^2}{R}. \tag{1-7}$$

Franklin first established the convention for electric current flow in the external circuit of a battery by assuming the direction to be from the positive to the negative terminal, whereas we now know that the electrons move in the opposite direction. Since the original convention is still in standard use, current flow will be shown in this text as flowing from the positive to the negative terminals in circuits external to a generator or battery.

When an electric current flows through a conductor, a magnetic field, having a magnitude depending on the value of the current, surrounds the conductor. The magnetic effect is greatly increased if the conductor is wound in the form of a coil and particularly if it is wound on an iron or steel core. The ability of a coil or a conductor to produce a magnetic field is termed *inductance,* and the circuit element is known as an *inductor.* A magnetic field causes the attraction of adjacent ferrous materials, and the effect is utilized in the construction of relays, magnets, and motors.

An electric field exists between two conductors when a positive

charge is placed on one and a negative charge on the other. If the conductors are in the form of plates with an insulating material, in this case called a dielectric, between them, the electric field is enhanced. Such a device is termed a *capacitor*. The *capacitance* C is evaluated in farads and is given by the relation

$$C = \frac{Q}{E}, \tag{1-8}$$

where Q is the charge in coulombs and E is the difference of potential in volts across the plates.

The electric field of a capacitor depends on the area of the plates that "see each other," the dielectric constant of the material between them, and the separation of the plates. Except for possible leakage, no current flows through a capacitor when the applied voltage is steady or direct. However, if the applied voltage changes, the number of electrons on the plates changes, and, consequently, a varying or alternating voltage produces a corresponding electron movement, that is, a current that flows in the capacitor circuit.

1-3. Conduction through Liquids

Solutions that conduct an electric current are termed *electrolytes*. They usually consist of aqueous solutions of an acid, base, or salt. Certain fused salts are also electrolytes. The conduction of a current in electrolytes differs from that in metals because the atoms are not fixed in position; they are mobile. An electrolyte disassociates into positive and negative ions which move under the action of an electric field. If two plates or electrodes, connected to a sufficiently high voltage, are inserted in an electrolyte, the positive ions move toward the negative electrode, or *cathode*, and the negative ions move toward the positive electrode, or *anode*. When the positive ions reach the cathode, each ion combines with an electron to produce a neutral atom. The negative ions, on the other hand, simply discharge electrons when they reach the anode. The generator or battery keeps the electrodes at the proper potential and transmits the electrons through the external circuit.

The conduction of electricity through electrolytes forms the foundation for the vast field of electrochemistry. The acidity or alkalinity of conducting solutions may be determined in terms of

their hydrogen or hydroxyl concentration, and the electrochemical potentials of various metals and oxides are frequently used in chemical analyses. Large numbers of dry cells and storage batteries annually produce an enormous amount of electrical energy from chemical energy. The inverse process, that is, the utilization of electrical energy in chemical industries, finds application in electroplating, in the electrolytic refinement of copper and other metals, in the reduction of aluminum and magnesium from their oxides, and in innumerable other processes.

1-4. Conduction through Semiconductors

There are many materials, such as metallic oxides, carbides, and sulphides, which are classed as *semiconductors* because they have a high specific resistance and a large negative temperature

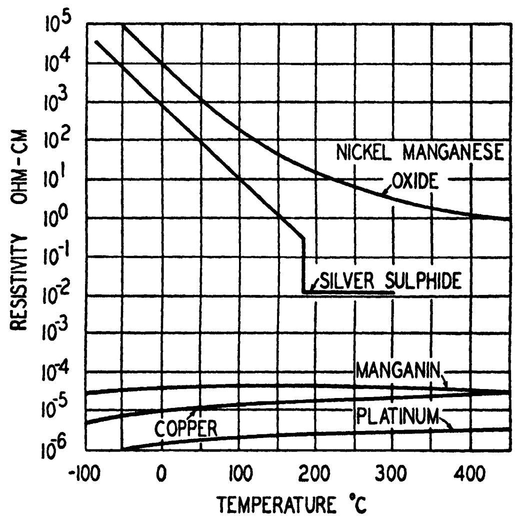


FIG. 1-5. Resistance-temperature characteristics of representative semiconductors and metallic conductors. *Courtesy Bell Telephone Laboratories, Inc.*

coefficient. In Sec. 1-2 mention was made of the fact that the resistance of a metallic conductor increases with rising temperature; for annealed copper wire the increase is about 0.4 per cent per degree C. Special alloys, such as Manganin, have practically no temperature coefficient; they are used in resistance boxes and for standards. Semiconductors, however, decrease markedly in

resistance as the temperature increases, and their resistances may also vary, depending on the previous history.

The name *thermistor,* derived from the words thermal resistor, is applied to a circuit element of the semiconductor type. Curves of Fig. 1–5 show the variation of resistance with respect to temperature of representative conductors and semiconductors. A group of thermistors, designed for application in telephone circuits, is illustrated in Fig. 1–6.



FIG. 1–6. Typical thermistors used in telephone communication circuits. *Courtesy Bell Telephone Laboratories, Inc.*

Thermistors were considered many years ago for application as a fire-detection device. The element was made by fusing a small bead of the temperature-sensitive material around two interlinked loops of wire, which acted as the leads, and mounting it in a small glass tube similar to an automobile fuse. It was connected in series with a relay to a source of alternating voltage. When the unit was heated, its resistance decreased abruptly, the relay was energized, and this, in turn, closed a pair of contacts in an alarm circuit. The resistance of the thermistor was controlled solely by the ambient temperature in view of the fact that the current through the thermistor was so low that it contributed only a negligible amount of heat.

In a modification of this application, the external resistance is made very low in comparison to the thermistor resistance. As the resistance of the thermistor decreases, it is heated more and more by the current flowing through it. This brings about a still

further reduction of the resistance until the current through the thermistor is limited by the external resistance of the circuit or until relay contacts interrupt the circuit. A device of this type is useful as a time-delay relay or switch. In an alternative indirect-heating method, the thermistor in a control circuit is placed adjacent to a heating coil connected in the operating circuit. The operating and control circuits are electrically independent in such an installation.

Thermistors obey Ohm's law in the same manner as metallic resistors, provided that the temperature remains constant. It is the change in temperature of these devices that causes the nonlinear relationship of current with respect to voltage. Certain thermistors, such as those made of silver sulphide or uranium oxide, yield reproducible results only when they are used in a-c circuits; polarization effects, similar to those encountered in electrolytes, take place when they are used in d-c circuits. Thermistors made of a mixture of nickel and manganese oxides do not polarize and are, therefore, equally stable when used in either a-c or d-c circuits.

Silicon carbide and red cuprous oxide are representative semiconductors that have resistance values which are a function of the applied voltage. Circuit elements of this type are known as *varistors*. A typical resistance-voltage characteristic of a varistor disc made of silicon carbide and clay is shown in Fig. 1–7(*a*). Units of this type are used as protective devices against overvoltage on switchboard lamps in telephone exchanges. Varistors are also utilized as lightning protectors or arresters on power lines; they are connected between the high-tension power lines and the ground. Normally no power current flows to ground because of the high resistance of the arrester, but when lightning strikes the line, or when a high-voltage surge occurs on the line, the surge finds a path to ground through the momentarily lowered resistance of the arrester.

The copper oxide varistor has an additional, very useful property discovered by L. O. Grondahl in 1920: the conductivity may be as high as 10,000 times greater in one direction than in the other. The relationship of resistance versus potential difference across a typical unit is shown in Fig. 1–7(*b*). The curve discloses that the device passes current principally in one direction whereas metallic resistors conduct current equally well in

both directions. The low-resistance path through the copper oxide varistor is from the oxide to the copper; that is, the unit

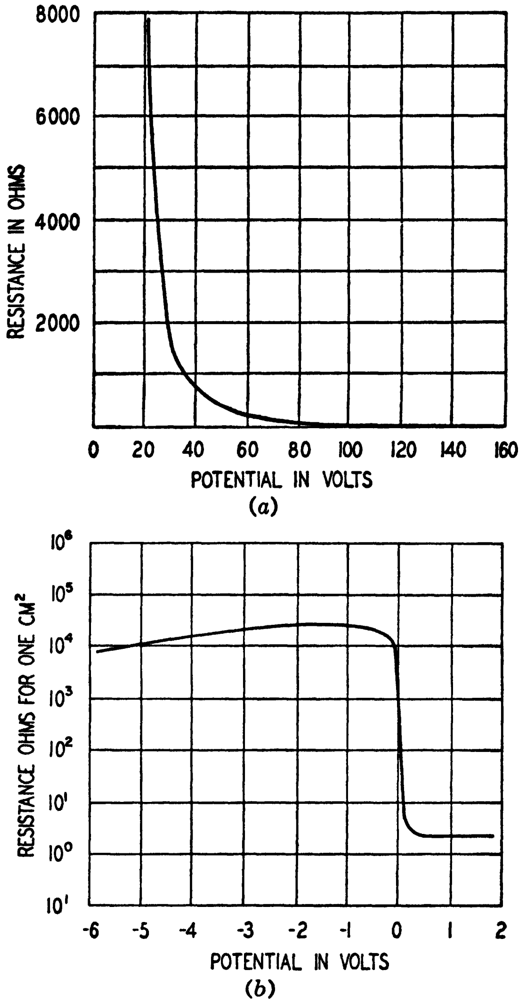


FIG. 1-7. (*a*) Resistance-voltage characteristic of silicon-carbide ceramic varistor; (*b*) resistance-voltage characteristic of copper-oxide varistor. *Courtesy Bell Telephone Laboratories, Inc.*

conducts when the terminal on the copper has a negative polarity with regard to the terminal on the cuprous oxide. Varistors are usually made from very pure copper, punched in the form of

plates or washers. They are heated in air to a high temperature to form the cuprous oxide and then go through a special quenching technique. One side of each disc is masked to prevent formation of the oxide during heating, or the oxide is removed to allow for circuit connection directly to the copper. Soft lead foil, a colloidal graphite layer, or a plated coating makes contact with the oxide surface for the other electrical connection. The theory underlying the copper oxide varistor is still incomplete, but it is believed that the physical nature and the formation of the junction or barrier layer between the copper and the oxide are primarily responsible for its strange behavior.

1–5. Dry-plate Rectifiers

The unilateral conductivity principle of a properly joined area of copper and cuprous oxide has been applied extensively in dry-plate rectifiers to convert alternating to direct current. More recently the selenium rectifier, consisting of a selenium oxide layer deposited on a steel plate, has been developed. Rectifiers of the dry-plate type are of considerable importance in electronic circuits because they are simple and reliable, have no moving parts, and have a low voltage drop with corresponding high efficiency, particularly when they are used on three-phase circuits. Their life is measured in years.

The static volt-ampere characteristic is obtained by impressing direct voltages across the rectifying element and reading the corresponding currents. Two sets of data, such as the ones plotted in Fig. 1–8, are obtained, one for the forward or conducting, the other for the reverse or nonconducting, connection. It is apparent that the reverse current is practically zero and that the forward current reaches high values for low applied voltages. The area of the discs is increased for high-current applications in order to keep the heating effect to a reasonable value; a number of the plates are connected in series for high-voltage applications. Copper oxide rectifiers have been built for voltages as high as 100 kilovolts, requiring many thousands of discs in series, and also for currents as high as 5000 amperes, where a number of large plates are connected in parallel. These rectifiers, however, are most commonly used to charge storage batteries and to supply low d-c voltages for electronic circuits. Ordinarily, $1\frac{1}{2}$-inch discs are used for this purpose; discs with

diameters of $\frac{1}{4}$ inch or less are utilized in a-c voltmeters that employ ordinary d-c meter movements.

Copper oxide and selenium rectifiers are electronics devices; they have no time delay in their operation. The current flows instantly when a voltage is applied and at the expected rate irrespective of the portion of the cycle on which the circuit is closed. The barrier layer causes the rectifier element to exhibit

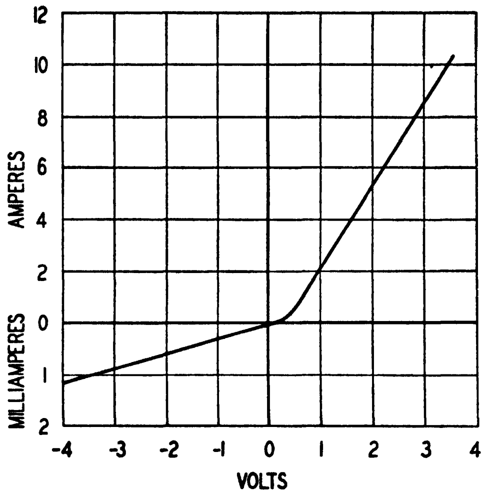


FIG. 1–8. Current-voltage characteristic of copper oxide rectifier.

a small but measurable capacity. This is of no importance at ordinary power frequencies, but when the rectifier is used on frequencies of 1000 or more cycles per second the physical size of the rectifier is reduced as much as possible to minimize the capacitance effect.

Four of the more common half- and full-wave connection diagrams for single- and three-phase circuits are shown in Fig. 1–9. The average value of one loop of a sine wave is 0.636 of the maximum value, and the effective or root-mean-square value is 0.707 of the maximum. The average value of current of one loop in a single-phase half-wave rectifier circuit is $0.636I_m$, which when evaluated over a complete cycle yields one-half of this, or $0.318I_m$. Similarly, the average voltage is $0.318E_m$, and, since E represents the effective value, the average voltage across the load is $0.450E$. The calculations for three-phase circuits are more

complicated; they may be found in textbooks on a-c theory. Dry-plate rectifiers are capable of top efficiencies of 65 per cent in single-phase and 85 per cent in three-phase circuit applications.

Any metallic structure, such as a steel pipe, lead cable sheath, or storage tank, when placed in an electrolyte like wet soil, sets

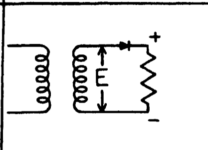
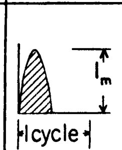
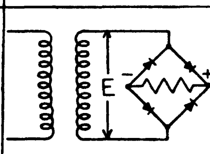
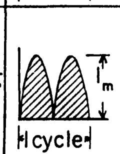
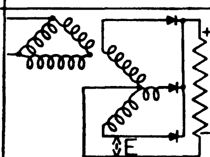
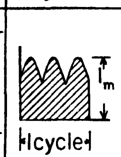
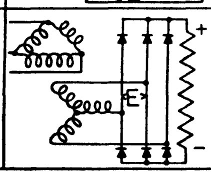
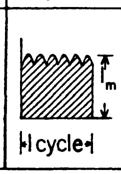
CIRCUIT	CONNECTION DIAGRAM	OUTPUT WAVEFORM	LOAD E_{avg}	LOAD I_{avg}
SINGLE-PHASE HALF-WAVE			$0.318E_m$ $0.450E$	$0.318\ I_m$
SINGLE-PHASE BRIDGE CIRCUIT			$0.636E_m$ $0.900E$	$0.636\ I_m$
THREE-PHASE HALF-WAVE			$0.827E_m$ $1.170E$	$0.827\ I_m$
THREE-PHASE BRIDGE CIRCUIT			$1.650E_m$ $2.340E$	$0.955\ I_m$

FIG. 1–9. Dry-plate rectifier circuits for single- and three-phase applications with data for half- and full-wave rectification.

up a flow of current from one portion to another or to other metallic bodies, analogous to local action in a battery. Stray currents from electric railways or grounded power lines contribute to this action. Small quantities of the metal go into solution at the anode where the current leaves the structure. This causes pitting, deterioration, and ultimate failure of the structure. Corrosion is avoided by reversing the current, that is, by making the structure cathodic instead of anodic. Zinc is higher than iron in the electrochemical series, and, therefore, if it is applied to iron, it makes the iron cathodic and prevents corrosion. The

product is known as galvanized iron; it is used in the construction of ship hulls and as a roofing material.

A more efficient and economical method of counteracting corrosion in buried structures is obtained by causing a direct current to flow from an outside source in the opposite direction so as to make the contacting soil or water anodic and the structure cathodic. As shown in Fig. 1–10, the positive terminal of a full-

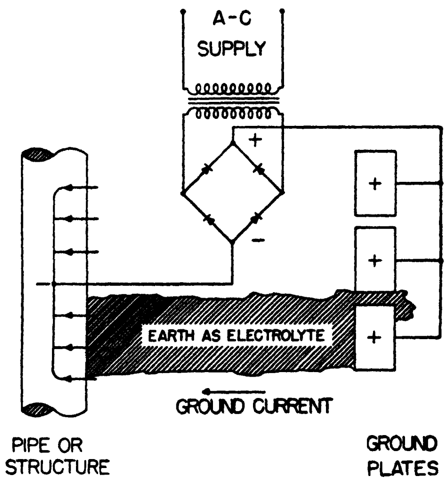


FIG. 1–10. Diagrammatic representation of cathodic protection for pipe lines.

wave dry-plate rectifier is connected to buried metal scrap or plates and the negative terminal to the structure requiring protection. A typical selenium rectifier used for cathodic protection is shown in Fig. 1–11. Voltage adjustment is made on the front panel to suit soil conditions, and the current is also adjusted to the proper value demanded by the particular installation. In 1942 over 3000 miles of cathodically protected petroleum pipe lines utilized in excess of 750 rectifiers.

Cathodic protection is also applied to prevent rust in water tanks, standpipes, and hot wells. The positive terminal of a small rectifier is connected to a group of stainless-steel or carbon electrodes suspended inside the tank; the negative terminal is connected to the structure. Experience has shown that a current of about 3 amperes is necessary to prevent the rusting of each 10,000 square feet of submerged metal surface.

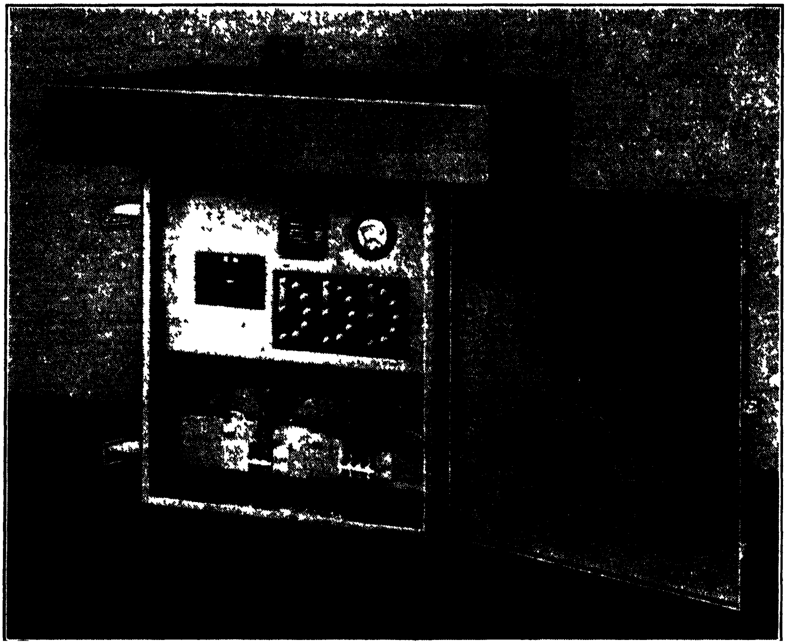


FIG. 1-11. Cathodic-protection rectifier of the selenium type. *Courtesy Federal Telephone and Radio Corporation.*

1-6. Conduction through Gases and in a Vacuum

Air at ordinary barometric pressures is a good insulator, and it is fortunate that this is so; the transmission of electrical energy would be impossible if the air were a good conductor. Air and gases under pressure ionize with difficulty. The insulating quality of the air, however, becomes impaired when very high voltages and consequent ionization come into play, as they do during lightning flashes. On the other hand, a high vacuum is also an outstanding insulator.

Conduction through a gas may be analyzed by considering two electrodes, a cathode and an anode, sealed in a glass envelope wherein the gas pressure may be varied. The electrodes, of equal dimensions and the same shape, are connected to an adjustable voltage supply. Gases and vapors contain a number of free electrons which move toward the anode under the action of the electric field, and if the voltage is low the electrons will be swept out gradually from the space between the electrodes.

The action is different, however, if a high voltage is applied to the electrodes. When an electron with the charge e in coulombs passes through a difference of potential of V volts, the total potential energy Ve in joules manifests itself as kinetic energy having a value of $\frac{1}{2}mv^2$ joules, where m is the mass in kilograms and v is the velocity in meters per second of the electron. The energy conversion is given by the equation

$$Ve = \tfrac{1}{2}mv^2 \quad \text{joules.} \tag{1-9}$$

By substituting values of the mass and charge of the electron and solving the equation for velocity, we obtain

$$v = \sqrt{\frac{(2)(1.60 \times 10^{-19})V}{9.11 \times 10^{-31}}} = 5.94 \times 10^5 \sqrt{V}, \tag{1-10}$$

where v is the velocity in meters per second of the electron, and V is the potential drop in volts through which the electron moves. If V in Eq. 1–9 is made equal to unity, the potential energy possessed by an electron that moves through a potential difference of 1 volt is equal to 1.60×10^{-19} joule. This convenient unit of energy is termed an *electron volt*. Only about 3 electron volts are required to decompose a molecule of water into hydrogen and oxygen; approximately 100,000 electron volts are needed to dislodge an electron from the innermost shell of a lead atom; but nearly 20,000,000 electron volts are required to remove a neutron from the nucleus of the carbon isotope 12.

An electron in an electric field and in gases under ordinary pressures acquires velocity, but it soon encounters neutral gas atoms which impede its movement and temporarily deflect it from its course. This accounts for the gradual sweeping-out action mentioned above, particularly if the voltage on the electrodes or the corresponding *potential gradient*, that is, the voltage drop per unit length of space between the electrodes in the gas, is quite low.

With a reduced gas pressure and the same potential gradient, any given electron again acquires energy as it falls through the difference of potential, but now its energy may increase until it is sufficient, on colliding with a neutral gas atom, to displace an electron from one shell to the next, producing excitation. Still greater rarefaction of the gas permits the electron to accumulate

sufficient energy in the same electric field to cause complete removal of an electron from a neutral atom, that is, ionization. Ionizing potentials in terms of equivalent volts, as well as other pertinent data of some elements, are given in Table 1.

TABLE 1

Element	Atomic Number	Symbol	Ionizing Potential	Shell Distribution of Electrons	Radiation When Excited
Hydrogen	1	H	13.53	1	Pink
Helium	2	He	24.46	2	Yellow, white
Nitrogen	7	N	14.48	2–5	
Neon	10	Ne	21.47	2–8	Red
Sodium	11	Na	5.12	2–8–1	Yellow
Argon	18	A	15.68	2–8–8	Blue, violet
Krypton	36	Kr	13.93	2–8–18–8	Deep blue
Xenon	54	Xe	12.08	2–8–18–18–8	Bright blue
Cesium	55	Cs	3.87	2–8–18–18–8–1	
Barium	56	Ba	5.19	2–8–18–18–8–2	
Mercury	80	Hg	10.39	2–8–18–32–18–2	Blue, ultraviolet

It is the energy imparted to the electrons in an atom that causes excitation and ionization, and, therefore, these effects are also produced with higher gas pressures if the potential gradient is increased correspondingly. In any event, the process continues after it has been initiated. Each electron released from a neutral atom becomes a new projectile by falling through a difference of potential; it collides with another atom, releases another electron, and so forth. The electrons travel toward and are delivered at the anode, while the positively charged remaining portions of the the gas atoms, or positive ions, migrate to the cathode where they pick up electrons and are reformed into neutral atoms.

In brief, the difference between conduction in a gas and in a vacuum is that *conduction is accomplished by electrons and ions in a gas but only by electrons in a vacuum.*

After conduction has been started in a gas-filled tube the process is cumulative, and unless a current-limiting resistance is used in the circuit the current may reach large and destructive values. The current-voltage characteristic of a gaseous tube is shown in Fig. 1–12.

The tube contains some free electrons and ions, which, when a low voltage is applied, move toward the electrodes of opposite sign; the current is of the order of a microampere or less. At a

higher applied voltage breakdown takes place, and the radiation that accompanies ionization is characteristic of the particular gas in the tube. If the external resistance is low, the current increases rapidly. As the voltage is still further increased, the current continues to rise and the discharge changes from a glow

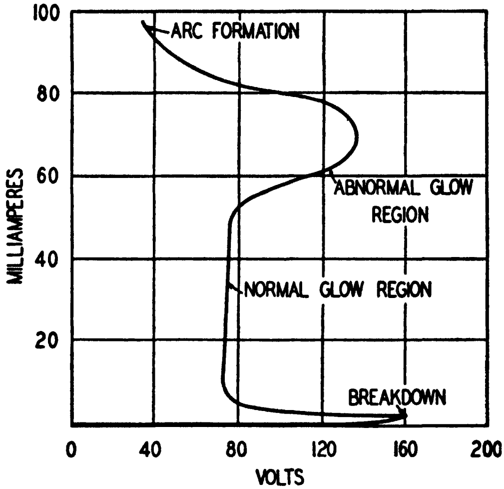


Fig. 1–12. Current-voltage characteristic of a gaseous tube.

into an arc discharge that has a low voltage across it. The glow-discharge principle is utilized in signs, fluorescent lamps, and glow tubes; the arc discharge of a gaseous tube finds its chief application in mercury-arc rectifiers.

1–7. Glow Discharge

When a direct voltage in excess of the breakdown voltage is applied to the plane parallel electrodes in a tube filled with gas at a pressure of a millimeter or less of mercury, a glow discharge appears, as is illustrated in the upper portion of Fig. 1–13.

A velvet-like glow covers the cathode. Next to this we see the faintly visible cathode, or Crookes, dark space, which is followed by a more luminous region, the negative glow. Then follows a much longer dark space, termed the Faraday dark space, and this in turn is followed by the luminous positive column or plasma, the color of which is determined by the particular gas or vapor. Most of the voltage drop along the tube occurs in the

cathode dark space. This is shown in the lower part of Fig. 1–13, where the potential along the discharge is plotted, starting from the cathode. If the tube is reduced in length and the gas pressure remains constant, the various portions of the discharge retain their length and positions with the exception of the posi-

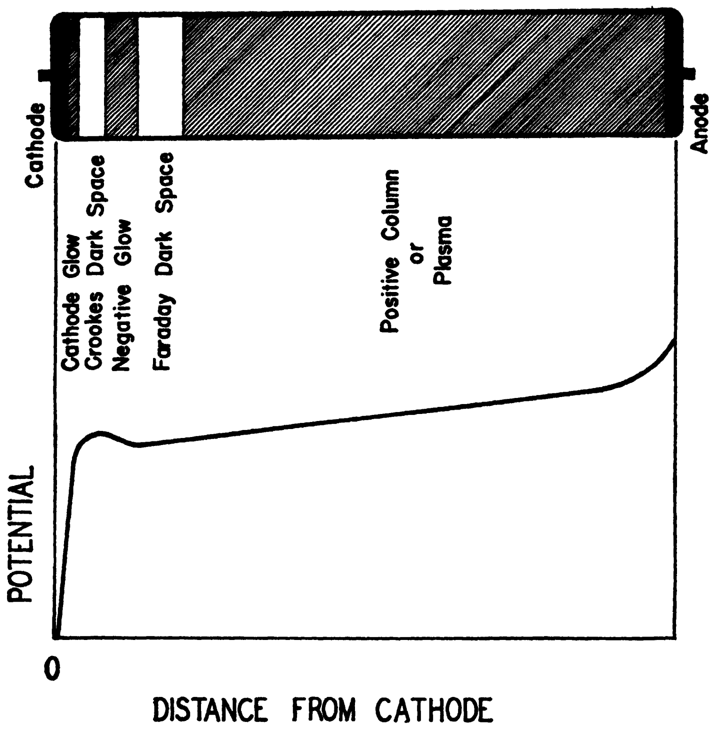


FIG. 1–13. Luminous spaces and drop of potential within a gaseous tube. Cathode used as reference electrode.

tive column, which gradually shortens until it disappears. After this the other portions vanish in turn, and only the cathode glow remains in a very short tube. A glow discharge is initiated at a certain voltage depending on the electrode material, electrode geometry, kind of gas and pressure, and distance between electrodes; it is sustained at a lower voltage than the starting voltage.

The space adjacent to the cathode is known as the *positive-ion sheath.* The electrons move rather quickly toward the anode, but

the positive ions, containing nearly all the mass of the gas atoms, move very much more slowly toward the cathode. This results in a concentration of positive ions around the cathode. A high positive-ion concentration or a high potential gradient has the tendency to remove electrons from the surface of the cathode, and certain materials, treatments, and coatings facilitate this action. Cathodes of this type are termed *cold cathodes* to differentiate them from cathodes that are heated.

The relatively slow-moving but massive positive ions strike the cathode, and when the potential gradient is high they release considerable energy; this causes cathode erosion and deterioration. Cathode material is gradually worn away because of this bombardment and is deposited on the walls of the tube. This process, known as *cathode sputtering*, is used to advantage to fabricate high-valued resistors, to produce a noble-metal coating on that portion of aluminum microphone diaphragms where the granular carbon comes in contact with the metal, and in other products. Materials such as gold, platinum, or carbon are commonly sputtered onto the base material. The WL-756 is a special tube which contains a helical glass coil sputtered with carbon and which is made in any desired resistance from 10 to 1,000,000 megohms.

1-8. Neon Lamps and Signs

During recent years gaseous tubes have found wide application in advertising. The favorite gas is neon, which produces a red light, but other gases or mixtures of gases that produce different colors are also popular. Often, too, the tubes are made of colored glass. Pressures from 6 to 12 millimeters of mercury are common with neon, but helium and certain gas mixtures require a pressure only half as great to produce an intense light. The tube is generally made long because the voltage drop occurs mainly in the cathode dark space, the length of which is very short compared to that of the luminous positive column. Luminous tubes commonly require an operating potential of 100 to 200 volts per foot of tubing length. Since the two electrodes are made identical, either one can serve as the cathode or anode, and tubes of this type can be operated on a-c or d-c circuits. The sign is usually fabricated so that a given tube length produces one or more letters of the sign; thus a certain gas pressure

and a definite applied voltage become standard. A suitable opaque coating forms the spacing between letters and is applied to the ends of the tube. Usually two or more tubes are connected in parallel across the high-voltage source.

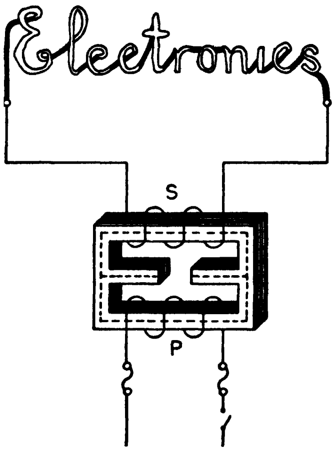


FIG. 1–14. Circuit diagram of a magnetic-leakage transformer connected to a luminous sign.

After the glow discharge has been started, it is maintained by a much lower voltage, and, consequently, gaseous tubes are customarily supplied by magnetic-leakage transformers. The magnetic circuit of these transformers, Fig. 1–14, is designed so that the secondary winding delivers a given voltage on open circuit, but, when current flows, the voltage is much lower owing to the bypassing of the magnetic flux that links the secondary winding. Such designs, as well as other methods that produce a higher initial than operating voltage, insure definite and prompt starting and also provide protection in the event of overload, such as arc formation within the tube. Transformers for luminous tubes are usually designed to supply 15,000 volts on open circuit; they deliver 30 milliamperes on short circuit.

1–9. Germicidal Lamps

Germicidal lamps are another class of tubes that contain mercury vapor and have cold cathodes. In a mercury-vapor tube from 18 to 24 per cent of the power input is converted into ultraviolet radiation. Over 80 per cent of the ultraviolet energy radiated at wavelengths between 2500 and 2600 angstrom units, the region of maximum bacterial effectiveness, is radiated at the 2537-angstrom-unit wavelength. Short wavelengths are measured in angstrom units, the unit being defined as 0.000,000,1 millimeter. The visible spectrum extends from about 3800 to 7600 angstrom units.

Ordinary glass does not transmit ultraviolet rays, and, therefore, the envelope must be of a special glass or quartz. Germi-

cidal lamps are made in tubular form; one of the largest is the 30-watt tube which is 36 inches long and 1 inch in diameter. A single lamp of this type will kill 90 per cent of the disease-producing germs in 700 cubic feet of air in 1 minute, or it will disinfect the air in a room 10 by 10 by 20 feet every 10 minutes. Figure

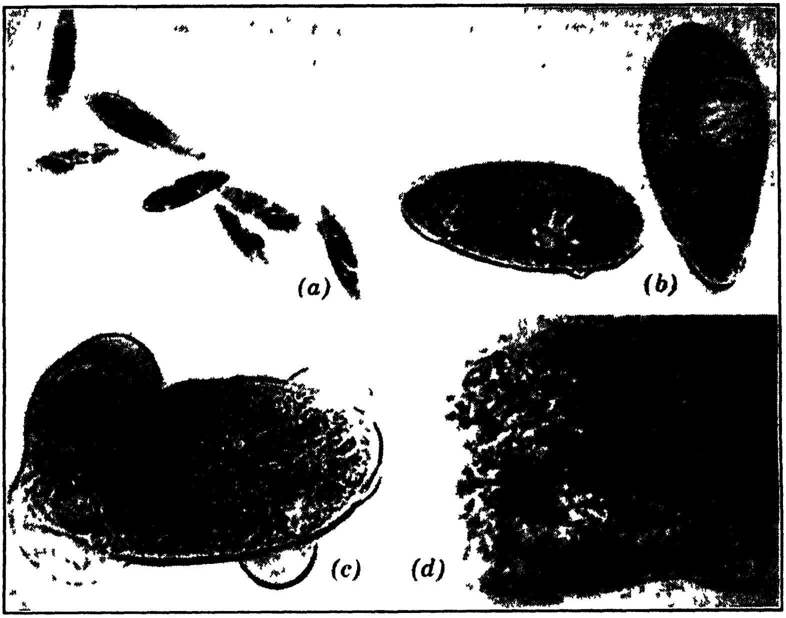


FIG 1-15. Action of ultraviolet radiation from Sterilamp on microorganisms (*a*) Normal paramecia; (*b*) same, showing distention after 30-second exposure; (*c*) swelling continues by weakening of cell walls; (*d*) cell dies after internal explosion *Courtesy Westinghouse Electric Corporation.*

1-15 illustrates the effectiveness of ultraviolet radiation in destroying microorganisms. Hospital tests in which a number of these lamps were used over an operating table showed conclusively that the number of post-operation infections due to airborne bacteria dropped very markedly. The lamps are also employed for isolation in common wards by creating sterile zones between patients having contagious diseases. Germicidal lamps prevent and control the development of bacteria, yeasts, and molds in food-processing plants such as bakeries, breweries, and dairies. In tenderizing beef, estimated savings of 20 per cent are made

because of the absence of molds and the prevention of dehydration.

The average operating temperature of germicidal lamps, with normal spacing over the active discharge portion of the lamp, is about 125° F at an ambient temperature of 70°, and the maximum temperature directly over an electrode is about 215°. Because of these low temperatures, the lamps lend themselves readily without fire hazard to applications in air conditioning. They are installed in air ducts, and their use eliminates or materially reduces bacteria and other living organisms in recirculated air.

1-10. Fluorescent Lamps

Before considering gaseous tubes in the illumination field, it may be well to review some of the terms used in that science. *Luminescence* is the general term applied to light obtained from materials operating at temperatures lower than incandescence. The material may be excited by radiant energy, electron bombardment, chemical or biochemical reactions, electrical discharges in gases, or other means. If the emitted light ceases immediately or in less than 0.000,000,01 second after removal of the excitation, the light process is known as *fluorescence;* if it persists for a longer interval it is termed *phosphorescence.* Solid luminescent materials used in the manufacture of fluorescent lamps are called *phosphors.* Some of the common phosphors are zinc orthosilicate or willimite, zinc beryllium silicate, calcium tungstate, and magnesium tungstate. Frequently a trace of manganese or copper is added to serve as an activator and to increase the efficiency of luminescence.

Nearly everyone has seen the colorful luminescent effects of fluorescent and phosphorescent materials excited by invisible, ultraviolet radiation, or the fluorescence of a cadmium tungstate or a modified zinc sulphide-coated screen excited by X rays during the fitting of a pair of shoes. An important, but less known, industrial process utilizes fluorescence for the determination of imperfections in machine parts. A suitable liquid, carrying the fluorescent material in suspension, is made to flow over the part under test. The particles lodge in cracks, cleavages, or flaws and outline the imperfections when the machine part is flooded with ultraviolet radiation.

A mercury-vapor tube emits a large percentage of its radiant

energy in the ultraviolet portion of the spectrum, and this effect is utilized to produce an efficient source of illumination by depositing a thin layer of phosphor on the inner wall of the glass tube. When irradiated, the phosphor emits characteristically colored visible light. The light covers a large area in contrast to an incandescent lamp, in which light and heat are radiated from a decidedly smaller area; it results in a more diffused, glareless source of light. The efficiency is higher because the electrical energy is converted into more visible, and less invisible, radiant energy.

A tube that is filled with mercury vapor with slight additions of neon and argon and that uses a zinc-beryllium-silicate phosphor coating is classified as a daylight fluorescent lamp. It produces 35 lumens per watt as contrasted to an incandescent tungsten lamp, which develops only 16. If a zinc-orthosilicate phosphor coating is substituted, the emitted light changes to green and the luminous output rises to 75 lumens per watt.

When fluorescent lamps are used on commercial a-c circuits, the glow discharge and the resulting fluorescence go on and off with each voltage pulsation, or twice during each cycle. This produces periodic illumination and an annoying flicker which is very noticeable in the presence of moving objects. The effect is avoided by using recently developed slightly phosphorescent coatings or by operating two lamps simultaneously with a phase-displacing element in one of the two circuits so that the current reaches its maximum value earlier in one lamp than in the other, as shown in Fig. 1–16.

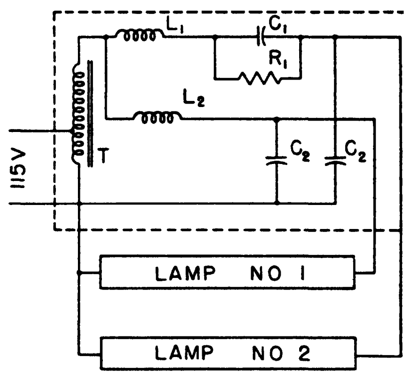


FIG. 1–16. Circuit diagram of a twin fluorescent lamp.

An autotransformer T, designed to deliver a momentarily high starting voltage, is connected to the two lamp circuits. One of these circuits includes a capacitor C_1 and a resistor R_1 to produce a phase displacement of the current in that circuit with respect

to the current in the other circuit. Two small capacitors, having values of about 0.006 microfarad, are each connected across the lamps to aid in the elimination of disturbances that might affect radiobroadcast reception. Possible arc currents are limited by the inductors L_1 and L_2, commonly termed choke coils. The normal operating voltage across each lamp is about 108 volts;



FIG. 1–17. Electrical machinery laboratory lighted to the wall by fluorescent lamps. *Courtesy Illinois Institute of Technology.*

however, a momentary surge of approximately 450 volts is required for starting.

Fluorescent lamps are made in various sizes from a few watts up to 100 or more; they range from 1 to 4 feet in length. Modern industrial installations of fluorescent lighting, which provide from 50 foot-candles in laboratories to 100 or more foot-candles on drafting-board surfaces, are shown in Figs. 1–17 and 1–18. In some installations, Fig. 1–19, fluorescent and incandescent lighting are combined to produce a pleasing high-intensity illumination. Tubes 8 feet in length were developed in 1945 for indirect lighting applications; by using certain mixtures of gases in

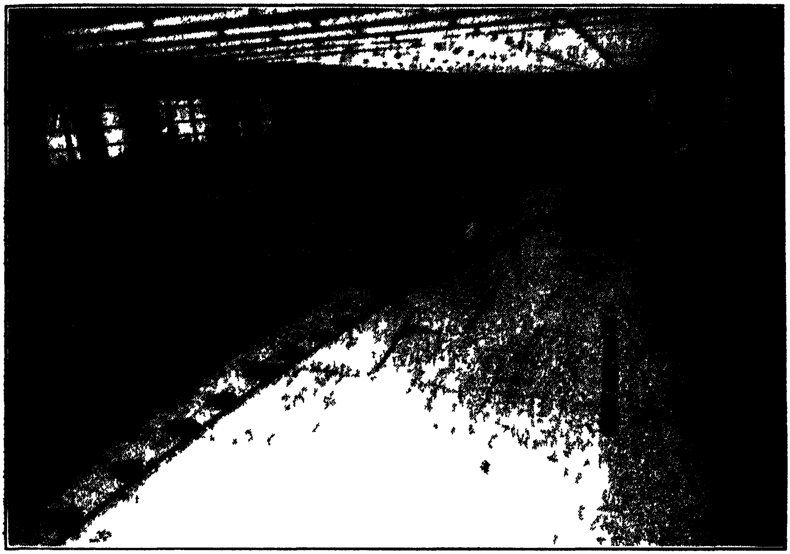


FIG 1-18 Drafting room lighted by continuous glass-enclosed fluorescent lamps *Courtesy Glen L Martin Company.*

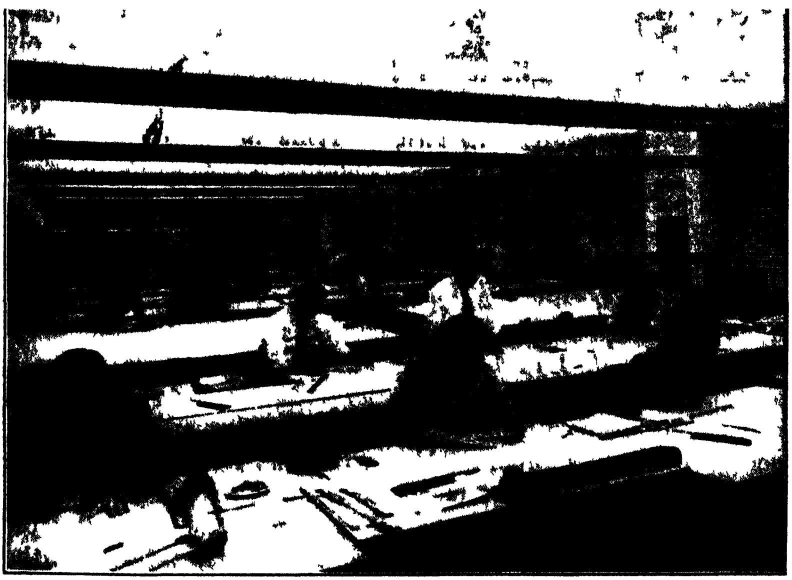


FIG. 1-19. Combined direct and indirect lighting in a modern drafting room. *Courtesy Glen L Martin Company.*

separate multiple tubes and by varying the applied potentials, one can obtain various colors and dim or bright illumination as desired.

1-11. Voltage-regulator Tubes

For certain values of gas pressure and electrode spacing, the discharge manifests itself only as the cathode glow, and such glow lamps, Fig. 1-20(*a*), are produced in many types and in various sizes up to 3 watts. The cathode fall of potential may be as low as 60 volts on d-c, or about 42 volts on a-c, circuits, and depends on the nature of the gas and electrode material; the current rating depends on the area of the electrodes and the pressure of the gas. A current-limiting resistor is placed in the base of the lamp. Neon or argon are generally used; during operation the cathode is covered with the glow characteristic of these gases. The normal operating brilliancy is approximately 0.8 candlepower per square inch of luminous surface. Lamps of this type are used as telltale and pilot lights to show circuit continuity. On a-c circuits, both electrodes glow; on d-c circuits, only the negative electrode glows, and so the lamp becomes a simple polarity indicator.

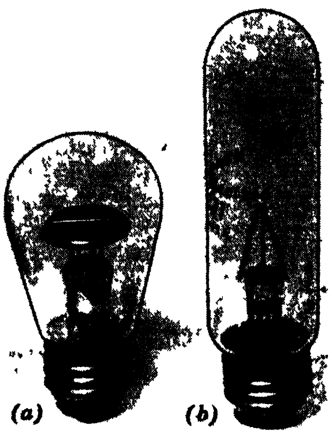


FIG. 1-20. (*a*) Typical glow lamp; (*b*) ballast or current-regulator tube

The graph of Fig. 1-12 showed that the voltage across a gaseous tube remains substantially constant after breakdown throughout a considerable current range. When such a specially designed voltage-regulator tube is used, Fig. 1-21(*a*), the voltage across the tube and connected load remains approximately constant even though the supply voltage fluctuates. The variable supply voltage is greater than the breakdown voltage of the tube; the difference between the supply voltage and that which appears as voltage drop across the tube and load exists across the

series resistor R_S. The connection x–x is sometimes used to obtain an adjustable constant low voltage from a high-voltage source.

Voltage-regulator tubes, when used on d-c circuits, are connected so that the larger electrode is the cathode; this provides an extended current range. Tubes of the same type may be connected in series to produce a group of stabilized voltages that are multiples of the voltage drop across a single tube; thus, as shown in Fig. 1–21(*b*), two VR-75 tubes produce regulated voltages of 75 and 150 volts. Dissimilar types of tubes cannot be

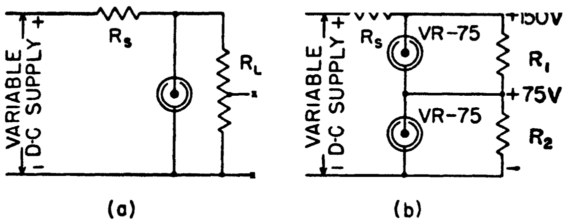


Fig. 1–21. (*a*) Circuit using a voltage-regulator tube; (*b*) two similar voltage-regulator tubes used in series.

used in series because of the differences which exist in their breakdown voltages and operating ranges. Voltage-regulator tubes usually have low current ratings.

A voltage-regulator tube must not be confused with a ballast, or current-regulator, tube, which consists of a resistance wire of nickel or alloy mounted in a tube filled with hydrogen. A typical ballast tube is shown in Fig. 1–20(*b*). It is a *series* device and depends for its operation on a changing temperature coefficient of resistance of the wire to keep the voltage across the load constant, whereas a voltage-regulator tube is connected in *parallel* with the load.

1–12. Simple Stroboscope

The luminosity of the light emitted by a glow-discharge tube, when operated in the normal glow region, is directly proportional to the current. This effect is utilized in the transmission of speech and music over a light beam and in the recording of sound on film. The electrical image of the sound pattern, that is, a voltage of variable frequency and changing amplitude, is im-

pressed on the primary winding P of a transformer, Fig. 1–22. A secondary winding S is connected to a glow lamp which receives an average current from the battery B; the current-limiting resistor R_S adjusts the current to the proper value. As the input voltage changes, the intensity of the light from the tube is modulated; that is, it varies from its normal value in accordance with the input voltage variations.

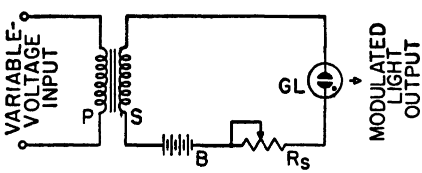


Fig. 1–22. Circuit diagram for conversion of variable-voltage input to variable-intensity light output. Dot in tube symbol indicates gaseous tube.

Standard glow tubes may be used for this purpose, but special tubes known as crater-type lamps have been developed that produce the discharge between the center electrode or crater connected as the cathode and an outer cylinder used as the anode. The high current density at the cathode produces a concentrated, easily focused source of light.

If an alternating voltage is impressed on a glow tube, the gas ionizes and becomes luminous when the striking potential is reached. The gas deionizes and the light is extinguished when the voltage drops to a value less than the striking potential. Ionization and deionization are effected in microseconds, and, consequently, such a lamp lights 120 times per second on a standard 60-cycle a-c circuit. When a shaft end or a disc on which a chalk mark has been made revolves at 1800 revolutions per minute and is illuminated by the glow lamp, the mark appears stationary but on each of the four quadrants. This happens because the shaft or disc is illuminated once for every 90° of its rotation and only during that period of time when the voltage applied to the lamp exceeds the breakdown potential and remains above the extinguishing value.

A glow tube may also be operated intermittently on a d-c source of supply by charging a capacitor through a resistor until the capacitor voltage reaches the striking voltage. The capacitor then discharges through the glow lamp and the process repeats. The circuit is shown in Fig. 1–23.

With no initial charge on the capacitor, the circuit is closed and the voltage across the capacitor then rises exponentially accord-

ing to the equation

$$V_c = E_B(1 - \epsilon^{-t/RC}), \qquad (1\text{-}11)$$

where V_c is the voltage at any instant across the capacitor during charge, E_B is the supply voltage, ϵ is the Napierian base (2.718), t is the time in seconds that has elapsed since the circuit was closed, R is the resistance of R in ohms, and C is the capacitance of C in farads.

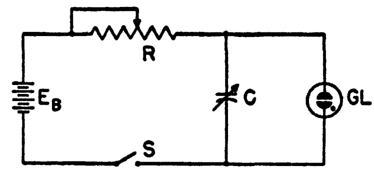


FIG. 1-23. Simple stroboscope circuit.

The voltage-time characteristic of the capacitor is shown by the heavy line in Fig. 1-24. When the voltage reaches V_1, which is the breakdown voltage of the tube, the tube fires and the capacitor discharges quickly to the extinction voltage V_2 where the gas deionizes. The capacitor then recharges and the cycle repeats itself.

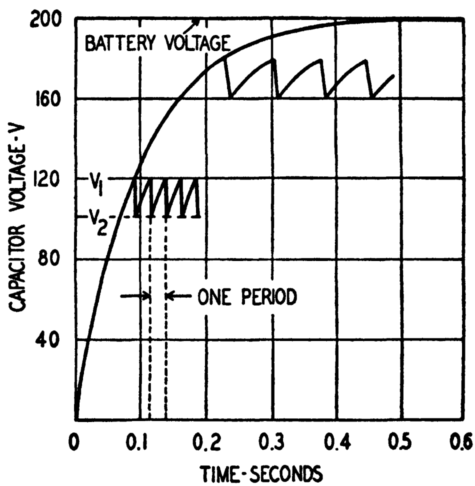


FIG. 1-24. Voltage-time variation of capacitor in a simple stroboscope circuit.

This circuit, known as a *relaxation oscillator,* produces oscillations having a period equal to the time required to charge the capacitor from V_2 to V_1 plus the discharge time from V_1 to V_2. Frequencies ranging from 1 cycle in 15 minutes to more than

10,000 cycles per second may be obtained by changing the supply voltage, the value of the resistor, and particularly the value of the capacitor. The waveform of the voltage across the capacitor approximates that of a saw tooth and depends on the supply voltage. With high values of applied voltage the waveform is very nearly triangular, whereas the waveform has a decided curvature when the supply voltage is only slightly greater than the breakdown voltage of the tube. Figure 1–24 shows this clearly.

By making the capacitor C variable, the device becomes a variable, periodic light source, termed a *stroboscope,* which can be used to indicate speed or to explore rapidly recurring mechanical movements. In the study of mechanical movements the periodicity of the stroboscope is adjusted so that the object under observation is illuminated once for every cycle of operation, but each successive flash of light is advanced slightly over the previous one. The mechanical movement then appears to go through its operation in slow motion and at a rate depending on the incremental advancement of successive illuminations.

Problems

1. A 110-volt battery, connected to a resistor, causes a current of 60 milliamperes to flow in the circuit. (*a*) Calculate the number of electrons that pass a given point per second. (*b*) What is the value of the resistor in ohms? (*c*) Calculate the power dissipated by the resistor.

2. What is the cost of heating the resistor in Problem 1 for a period of 6 hours, assuming that the cost of energy supplied by the battery is 12 cents per kilowatt-hour?

3. The technical literature on silicon carbide varistors states that the current through some of these materials varies as the fourth power of the applied voltage. Replot the data obtained from the graph in Fig. 1–7(*a*) to show how the instantaneous current varies with respect to the instantaneous voltage; calculate the exponent for E for that particular varistor.

4. Determine the velocity in miles per minute reached by an electron after it falls through a potential difference of (*a*) 5 volts, (*b*) 50 volts, (*c*) 500 volts, (*d*) 5 kilovolts.

5. Through what difference of potential must an electron fall so that its velocity is 15 per cent of the velocity of light, which is approximately 186,000 miles per second? At higher speeds than this the apparent mass of the electron increases appreciably.

6. Why does a carbon-filament lamp flicker less than a tungsten-filament lamp when operated on a 25-cycle a-c circuit? Does the same reasoning apply to the double fluorescent lamp shown in Fig. 1–16?

7. Draw a full-wave dry-plate rectifier circuit to be used for the prevention of corrosion in a power-plant hot well. Indicate electrode polarities.

8. Using as many as required of the three voltage-regulator tubes VR-75, VR-105, and VR-150, each of which has a voltage drop across the tube as given by the number, devise a circuit and list the regulated voltages that can be obtained from a variable-voltage source, the minimum of which always exceeds 330 volts.

9. A circuit similar to the one shown in Fig. 1–23 is connected with a 550-volt battery, a 1.2-megohm resistor, a 10-microfarad capacitor, and a glow tube that has a breakdown voltage of 120 volts and an extinction voltage of 90 volts. Plot the voltage across the capacitor with respect to time, as shown in Fig. 1–24.

10. On the assumption that the discharge time is negligible, develop an equation for the period T of the relaxation oscillator, Fig. 1–23, by substituting V_1 and V_2 in Eq. 1–11 and solving the two equations for the corresponding values of t.

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2.

The Hot-cathode Diode

The conduction of a current in the operation of glow tubes depends on the ionization of neutral gas atoms as the result of their encounter with accelerated free electrons. Glow-discharge currents are usually of low value, but in arc discharges very large currents may flow because of electron emission caused by the positive-ion bombardment of the cathode. In order to get a copious supply of electrons in a vacuum tube, that is, one in which the mean free path of an electron is greater than the distance between the cathode and anode, it is necessary to obtain a cathode that inherently emits electrons abundantly. This chapter deals with electron emission, cathode and anode constructions, and their use in a simple two-element tube or diode, also termed a *kenotron* if it is of the vacuum type, and a *phanotron* if it is gas filled.

2–1. Electron Emission

Any free electron in its random motion between atoms in the interior of a metallic conductor is not subject to an average force in any specific direction, and there is a large random interchange of electrons between atoms. However, a barrier exists at the surface because of the unsymmetrical arrangement of the charges about the nuclei of boundary atoms. If an electron attempts to leave the surface, an induced positive charge or image force that acts as a restraint on the electron will be produced in the conductor. The electron must overcome this force and must give up a definite amount of kinetic energy. The kinetic energy that must be imparted to an electron to permit it to escape from the metal

is known as the *work function* of the material; it is usually expressed in electron volts. The energy relations may be stated conveniently by means of Eq. 1–9, or

$$Ve = \tfrac{1}{2}mv^2 = \phi e \text{ joules,} \tag{2-1}$$

where ϕ is the voltage equivalent of the work function ϕe, and the other factors retain their previously assigned designations.

The voltage equivalents of some of the commonly used materials are given in Table 2. These experimentally determined values afford an index of the ease of electron emission.

TABLE 2

WORK FUNCTION VALUES

Material	ϕ in Volts	Material	ϕ in Volts
Platinum	5.0	Nickel	4 0
Tungsten	4.52	Thoriated tungsten	2.63
Carbon	4.5	Calcium	2.4
Mercury	4.4	Oxide coated	0.5–1.5

On the basis of Eq. 2–1 an electron in tungsten must possess kinetic energy to the amount of 7.23×10^{-19} joule, or it must reach a velocity of 1.27×10^6 meters per second, before it can escape.

The ordinary methods of electron emission are: (*a*) thermionic emission, (*b*) photoelectric emission, (*c*) secondary emission, and (*d*) high electric-field emission. Energy is supplied to release electrons in methods *a*, *b*, and *c*; in method *d* the surface barrier is modified so that electrons can escape.

Thermionic emission was the first method to be developed and is used at present in most of the electron tubes employed in telephony, radio, and television; it finds application in tubes used as low- and high-voltage rectifiers, oscillators, control devices, and instrumentation. Photoelectric emission is the basic principle of tubes that operate because of changes in light; this type of emission and the application of phototubes will be considered in Chapter 7. Emission methods *c* and *d* will be studied in connection with multielectrode and gaseous tubes in Chapters 4 and 6.

2-2. Thermionic Emission

When the temperature of a conductor is increased, the molecular, atomic, and electronic energies are increased until sufficient

energy is imparted to some of the electrons so that they are enabled to leave the surface. We define *thermionic emission* as the process in which electrons are evaporated from a solid or liquid conductor at elevated temperatures. The conductor may be heated easily and conveniently by means of an electric current. Since a low work-function surface permits the evaporation of electrons with less applied energy than is required for one with a higher value, less heating power needs to be supplied to such an emitter and this results in a higher *emission efficiency,* a term given to an arbitrarily established ratio of emission current to heating power.

At the turn of the century O. W. Richardson, using the analogy of evaporation at the surface of a liquid, developed an equation for electron emission. Later S. Dushman modified Richardson's equation into the form

$$i = AT^2\epsilon^{-b/T}, \tag{2-2}$$

where i is the electron current in amperes per square centimeter of the heated surface, A and b are constants, T is the temperature in degrees Kelvin (°C + 273) of the heated surface, and ϵ is the Napierian base (2.718).

Richardson's equation is an empirical formula with the constants A and b selected for any given material so that the equation fits the experimentally derived data. The work function of the emitter enters into the evaluation of the constant b in the following manner:

$$b = \frac{\phi e}{k} = 11{,}605\phi, \tag{2-3}$$

where ϕ is the voltage equivalent of the work function of the emitter, e is the electron charge in coulombs, and k is Boltzmann's constant (1.371×10^{-23} joule per degree K).

The value of b may be determined graphically by measuring the emission at various temperatures and then plotting the log i/T^2 against $1/T$. The resulting straight line has a negative slope of b. Values of A and b of some common materials used as emitters are given in Table 3.

Three emission curves are given in Fig. 2–1. They show that the emission current increases exponentially to an extremely large value as the temperature increases; the form of each curve

TABLE 3

CONSTANTS FOR RICHARDSON'S EQUATION

Material	A	b
Tungsten	60.2	52,400
Thoriated tungsten	15.5	33,200
Tantalum	60.2	47,200
Platinum	1.7×10^{-4}	72,500
Oxide coated	1.0×10^{-2}	11,600
Cesium	162	21,000

is determined almost completely by the exponential factor of Richardson's equation. Normal operating temperatures are indicated on each curve.

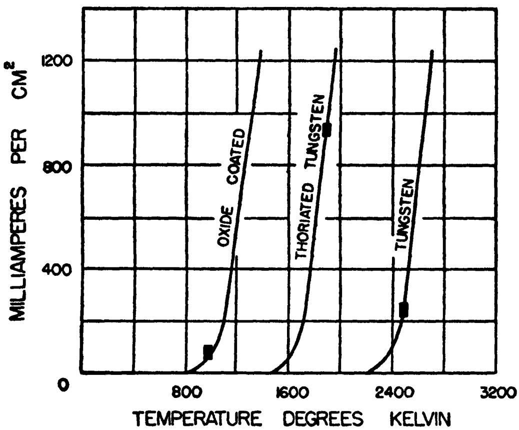


FIG. 2–1. Emission curves for three types of thermionic emitters.

2–3. Temperature and Voltage Saturation

Richardson's equation assumed that all electrons emitted by the cathode migrated toward the anode and that the number of emitted electrons depended only on the work function of the cathode and its temperature. Since the work function of an emitter is fixed, the anode current within a specific tube is a function of (*a*) the cathode temperature and (*b*) the anode-to-cathode potential, as will be shown shortly.

Electrons have little or no energy after being emitted by the cathode. Succeeding electrons encounter the repelling field of the previously emitted ones, with the result that for a given temperature a definite cloud of electrons, termed a *space charge,*

surrounds the cathode. This space charge is located very close to the cathode, and as the temperature of the cathode is increased the space charge increases correspondingly. If no potential difference exists between the anode and cathode, a state of equilibrium is reached; that is, the number of electrons emitted by the cathode is equal to the number that return to the cathode from the space charge. When the temperature of the cathode is increased, equilibrium is obtained again with a larger space charge.

If the anode has a positive potential with respect to the cathode, there will be an attractive force on the emitted electrons and their movement constitutes the anode current. When the cathode is at a low temperature all the emitted electrons move toward the anode, but if the anode voltage remains constant and the temperature is increased the current rises in accordance with

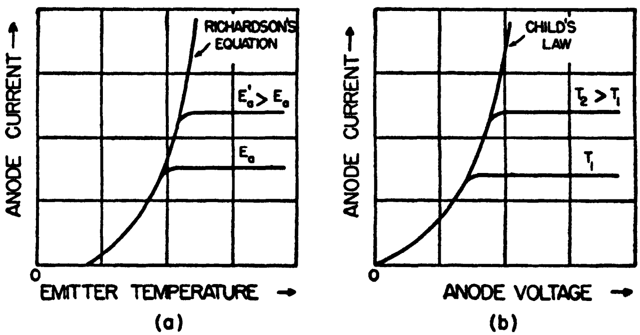


FIG. 2-2. (*a*) Graph showing Richardson's equation and temperature saturation; (*b*) graph showing Child's law and voltage saturation.

Richardson's equation. At a certain temperature a space charge begins to form at the cathode and the anode current reaches a constant value, as indicated in Fig. 2-2(*a*). This effect is known as *temperature saturation.*

On the other hand, if the cathode temperature is held constant and the anode voltage is increased, the current increases until practically all the emitted electrons arrive at the anode and the space charge is reduced to zero. At any higher anode voltage the anode current remains substantially constant. This effect, illustrated in Fig. 2-2(*b*), is known as *voltage saturation.* Because of slight variations in temperature and work function along the cathode, as well as variations in the electric field at the

cathode, the saturation curves show a gradual transition to a constant current.

The current-voltage relationship of a simple two-electrode vacuum tube is plotted in Fig. 2–2(*b*). It is known as *Child's law,* which states that the anode current varies as the $\frac{3}{2}$ power of the anode voltage provided there is an excess of electrons at the cathode.

Child's law is based on the assumptions that the two electrodes are plane, parallel, and constant-potential surfaces, that the electrons start from rest at the cathode, and that the anode current is limited by the space charge. The solution of a group of equations founded on these assumptions gives us the equation

$$I_a = 2.33 \times 10^{-6} \frac{E_a^{3/2} A}{d^2}, \qquad (2\text{–}4)$$

where I_a is the anode current in amperes, E_a is the anode potential in volts, d is the separation of the electrodes in centimeters, and A is the area in square centimeters of the heated surface.

The assumptions are seldom achieved in practice, and the exponent of E_a ranges between the values of unity and $\frac{5}{2}$. The nonlinear relationship of anode current to anode voltage places the two-element vacuum tube in the class of nonlinear resistances; as such it has found a number of applications. A two-electrode tube may also be used as a constant-current device when the cathode is operated at a constant temperature and above the voltage-saturation point as shown at T_1 in Fig. 2–2(*b*). X-ray tubes are commonly operated under these conditions, but ordinary tubes usually operate on the lower curved portion of any given characteristic.

2–4. Cathode Materials

Any material to be of importance as a cathode must maintain a uniform electron emission throughout a long life. Low operating temperatures with corresponding long life are obtained by using low-work-function emitters. Formerly 1000 hours of operation were considered a normal life, but improved manufacturing techniques and accurate production controls have increased emitter life to 5000 hours or more.

Economic operation necessitates the use of a low-work-function material; however, the material must also be self-supporting and

must not evaporate excessively at the operating temperature. It should be noted in this connection that the presence of gas atoms in a vacuum tube, particularly if the tube is operated with a high anode voltage, gives rise to positive-ion bombardment that causes rapid deterioration of the cathode.

Long cathode life also demands a constant filament temperature. Current-regulator tubes, mentioned in Sec. 1–11, are frequently used to hold the filament current constant on a fluctuating-voltage supply line; or a transformer of the magnetic-leakage type may be used to deliver a constant filament voltage.

The four major materials used as hot cathodes are: oxide-coated metals, thoriated tungsten, pure tungsten, and mercury-pool cathodes.

Oxide-coated Cathodes. In 1904 A. Wehnelt found that, by coating a high-melting-point core material with a combination of the oxides of barium and strontium, abundant electron emission is obtained at a temperature as low as 1000° K. The coating is usually applied to a nickel or nickel-alloy base in the form of carbonates and then heated to convert the carbonates to oxides. Life of an oxide-coated cathode generally terminates abruptly when either residual gases or those that develop as a result of hot spots contaminate the coating.

These cathodes are used almost exclusively in the manufacture of millions of radio and television tubes annually. The work function is low, as may be seen in Table 2, and their life is excellent. Although the coating is fragile, the tubes may be operated with anode potentials up to about 500 volts. At higher voltages the residual gases, which remain even in a highly evacuated tube, ionize, and the ion bombardment soon destroys the emissive coating.

Thoriated-tungsten Cathodes. Tungsten filaments are fabricated by pressing, heating, and swaging the powdered raw material into rods and subsequently drawing the heated rods into wire. In 1914 I. Langmuir discovered that the admixture of thorium oxide, which later is reduced to a monatomic layer of thorium on the surface of the tungsten, produces an electron emitter that has a lower work function than either thorium or tungsten. In the treatment of thoriated tungsten the material is heated or flashed for a short period of time at a temperature of about 2500° K; this changes some of the thorium oxide to

metallic thorium. At a slightly lower temperature the thorium gradually diffuses to a monatomic layer on the surface. The temperature of operation of the processed material is about 1900° K.

After an operating period, an emitter may lose some of the thorium layer and then the emission decreases; it is quite sensitive to the size of the thorium-coated area. The emitter contains thorium oxide internally and may be rejuvenated by repeating the temperature cycle. A manufacturing process known as carbonization protects an emitter of the thoriated-tungsten type against the results of positive-ion bombardment, that is, thorium evaporation. The emitter is heated in the vapor of some hydrocarbon such as alcohol or benzene, and this treatment results in an extremely hard tungsten carbide coating. Here the increase in operating temperature of the emitter results in a gradual reduction of the remaining thorium oxide, the diffusion of the thorium to the surface, and a much longer life.

Thoriated-tungsten cathodes are generally made in wire or ribbon form. Their greatest application lies in the field of medium-sized power tubes that use anode voltages between 500 and 3000 volts. The thoriated-tungsten surface is more firmly attached to the base metal than the coating on an oxide-coated emitter and can therefore be used on higher anode voltages without danger of destruction.

Tungsten Cathodes. Only a pure metal emitter is used when anode voltages of 3000 volts and above are required. Tungsten is the only suitable cathode material of all the metals and must, of course, have a high vaporization temperature and freedom from the effects of absorbed gases that influence the work function. It is operated at a temperature of 2500° K and finds its greatest application in large power and X-ray tubes.

Mercury-pool Cathodes. A mercury-pool cathode spot is obtained by initiating, through the aid of an auxiliary electrode, an arc discharge in the vapor between a mercury cathode and a fixed anode. The heat at the cathode spot vaporizes the mercury and maintains the vapor. Electrons are liberated; they collide with neutral vapor atoms, and form positive ions. So many positive ions are formed, even though many are neutralized by electrons at the cathode, that a high potential gradient exists at the surface of the mercury-pool spot. The electric field produces an attrac-

tive force, and a very large number of electrons escape. This, of course, results in a large current; the current density at the cathode spot is about 4000 amperes per square centimeter.

A tube or tank that uses a mercury-pool cathode is operated without heating delay, its efficiency is high, its overload capacity is very large, and, most important, the cathode does not deteriorate. These cathodes find application in large multiphase, low-voltage, high-current mercury-arc rectifiers used in the railway and electrochemical fields. More recently, individual single-phase units, termed *ignitrons,* which can deliver currents from 40 to 10,000 amperes, have been developed and applied extensively in rectifier, welding, motor, and control equipment.

2–5. Cathode Construction

Early cathodes were constructed as filaments; they were heated with an electric current just like an ordinary incandescent lamp. Filamentary cathodes are still used in d-c circuits, but when they were employed in radio tubes for operation on a-c circuits an objectionable hum was caused by the variation of the electron emission due to the changing filament temperature and the variable electric field between the filament and the anode. This resulted in the development of the indirectly heated cathode, which consists of a nickel or nickel-alloy sleeve with an external electron-emissive oxide coating and which is heated internally by means of an insulated, filament-type heater. The emissive coating of a filamentary cathode is sprayed directly onto the filament, which becomes part of the anode circuit. The heater of an indirectly heated cathode is insulated from the cathode, and only the sleeve is connected in the anode circuit. If the heat storage of the sleeve is made sufficiently large and if the heater is wound in a bifilar or double helical form, the anode current becomes constant. Indirectly heated cathodes require a longer initial heating time than filamentary cathodes. Both types are shown in Fig. 2–3.

The use of a hot cathode in a gaseous tube produces a large anode current; the internal resistance of the tube is extremely low because the anode voltage needs to be only slightly greater than the ionization voltage of the gas. For a mercury-vapor tube the voltage drop ranges from the minimum ionization potential of slightly more than 10 volts to the double ionization

potential of about 22 volts. In fact, a simple test for determining the merit of a cathode in a mercury-vapor tube consists in causing a momentary anode current of 150 per cent of the normal rated current to flow and reading the voltage drop across the

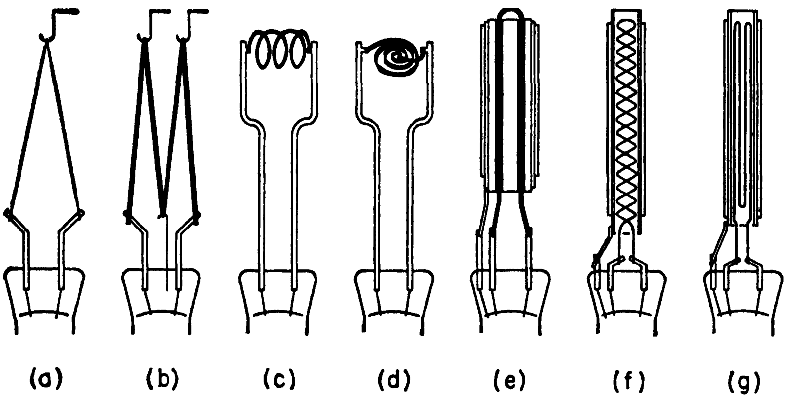


FIG. 2-3. Various forms of filamentary and indirectly heated cathodes.

tube. If the drop exceeds 22 volts, the cathode has lost much of its emissive ability and the tube is nearly at the end of its useful life. This test is important in checking tubes in industrial equipment where continuous operation is a major factor.

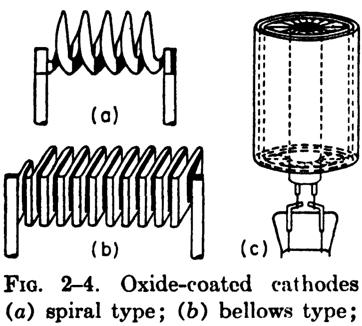


FIG. 2-4. Oxide-coated cathodes (*a*) spiral type; (*b*) bellows type; (*c*) heat-shielded cathode enclosed in concentric cylinders.

The application of oxide-coated cathodes to gaseous tubes leads to some very interesting designs. When an ionized gas surrounds a hot cathode, the space charge is largely neutralized by the positive ions, and electrons may be drawn or are emitted readily from deep slots and convolutions. Cathodes are made of oxide-coated ribbons and can be mounted as spirals or bellows, as shown in Fig. 2-4(*a*) and (*b*). The emissive surface is increased tremendously within a small space, but, more important, the heat losses are reduced owing to *heat shielding* and the emission efficiency is greatly increased. A heat-shielded cathode in which

a heater filament is enclosed in heat-conserving, concentric nickel cylinders is shown in Fig. 2–4 (*c*). Oxide-coated vanes are located at the top; they act as the emitting surface and as heat radiators. Cathodes of this type produce an electron current of 25 amperes or more. Large-area cathodes, however, have a tendency to flake off, and the coating evaporates gradually, particularly under large loads; this limits their life to several thousand hours.

Thoriated-tungsten and tungsten cathodes used in high-voltage power tubes are made in the form of filaments with round or rectangular cross section and have hairpin, M, helical, spiral, and other shapes.

2–6. Anode Materials and Construction

Superficially it would appear that almost any good conductor would be suitable for anode material; nevertheless, a number of requirements must be met. The material must radiate heat well; it must be capable of being degassed easily in the evacuation process in order to prevent later changes in operating characteristics; and it must have a high work function so that it does not act as an emitter at operating temperatures.

Electrons acquire velocity as they fall through a difference of potential, and when they strike the anode the kinetic energy is liberated as heat. The anode also receives by radiation a portion of the heat energy supplied to the cathode. Development of this heat requires a high-melting-point material, and iron, nickel, nickel alloys, and tantalum are commonly employed. These materials are carbonized or scrubbed with graphite to obtain a better heat-radiating and a higher work-function surface. Blocks or buttons of graphitic carbon are usually specified for gas-filled tubes; they can be made quite small because the low potential drop across the tube is synonymous with low heat-dissipation requirements. Neglecting the heat energy that strikes the anode by radiation, the anode or *plate dissipation* P_a in watts is given by the expression

$$P_a = E_a I_a, \tag{2–5}$$

where E_a is the anode potential in volts and I_a is the anode current in amperes. If either or both voltage and current vary, the instantaneous heat is calculated and averaged over an interval of time.

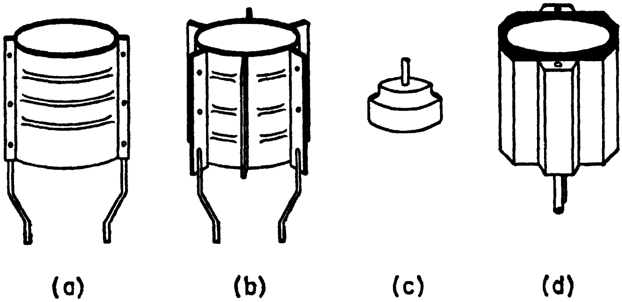


FIG. 2–5. Various forms of metallic and graphitic anodes.

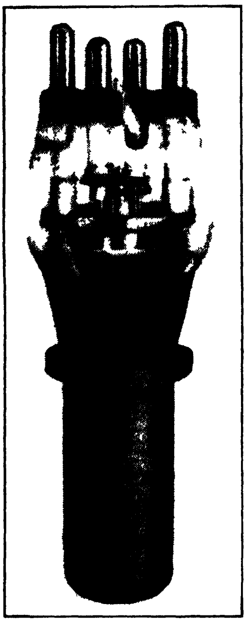


FIG. 2–6. Tube designed with external anode permitting that electrode to be water-cooled. *Courtesy Machlett Laboratories, Inc.*

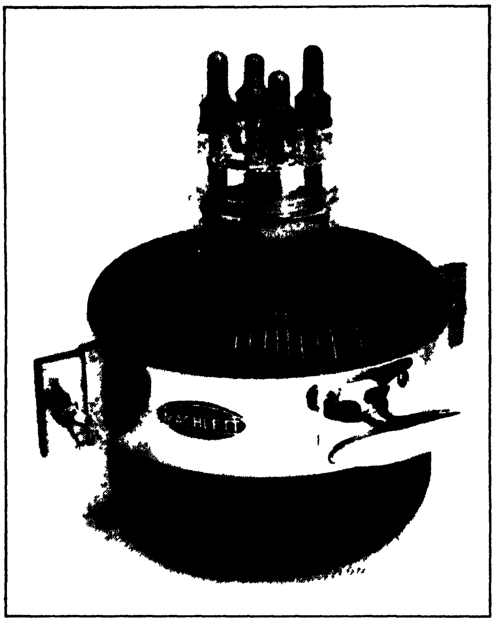


FIG. 2–7. Same type tube as shown in Fig. 2–6 arranged for air cooling. *Courtesy Machlett Laboratories, Inc.*

Small metal anodes are punched from sheet stock and formed into cylindrical or rectangular tubes to surround the cathode. Frequently, as shown in Fig. 2–5, they are ribbed or crimped for greater strength. Anodes for tubes that have ratings of 1 kilowatt or more are made part of the envelope by sealing the metal anode to the glass, as illustrated in Fig. 2–6. The circuit is connected with the anode at ground potential; this allows the anode to be cooled by circulating water, or, in an alternate application, the same tube can be used with a radiator for normal or forced air circulation, as shown in Fig. 2–7.

For anode voltages up to about 500 volts, the separation between the cathode and anode leads can be made easily by electrical connections through the press portion of the tube which supports these electrodes. Higher anode voltages, however, require that the cathode terminals be placed at one end of the tube and the anode terminal at the other.

A chemically active gas-absorbing substance, known as a *getter,* is used to eliminate any residual gas that may cling to the anode after the tube has been evacuated or to eliminate any gas liberated later during use. The getter consists of magnesium, barium, or a barium compound and is placed in a thin metal capsule or trough within the tube. After the tube has been evacuated and sealed the getter is evaporated by induction heating; some of it reacts at once with the remaining gas, and the residue is deposited on the walls of the tube where it is available to dispose of any future liberated gas.

2–7. The Vacuum Diode

During experimentation on electric lamps in 1882, Thomas A. Edison concluded that the blackening on the glass bulbs during use was due to carbon which evaporated from the filament. A year later he constructed a lamp with an extra electrode and discovered that an electric current flowed through the space between and from the hot filament to the extra electrode when the extra electrode was connected to the positive terminal of the d-c supply circuit. The term *Edison effect* is applied to this phenomenon which laid the foundation for electronics. In 1884 a patent, the first electronic application, was issued to Edison; in it he disclosed that the current in the extra electrode circuit varied greatly with the filament temperature and that the tube

could be used as a sensitive indicator for small changes in the supply voltage.

Since electrons can only flow from a hot cathode to the anode and not in a reverse direction, a simple two-electrode tube can be used as a rectifier on a-c circuits. Fleming in 1905 first applied the principle of vacuum-tube rectification to the reception of radiotelegraph signals.

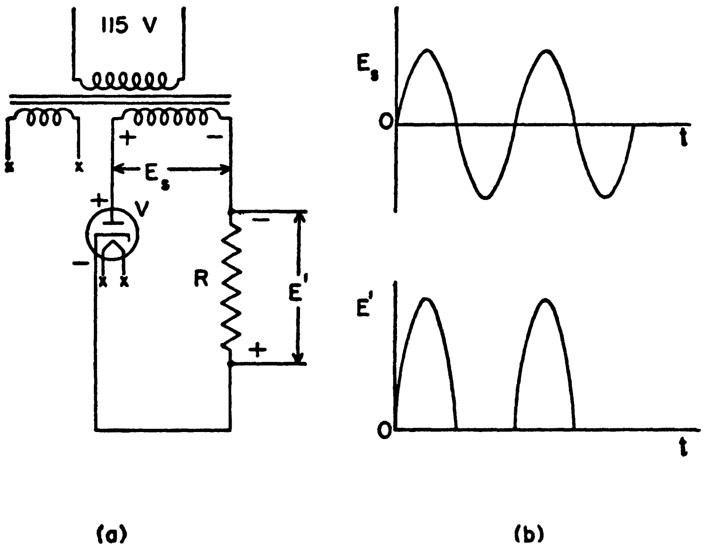


FIG. 2-8. (*a*) Basic vacuum-tube rectifier circuit; (*b*) transformer secondary voltage and voltage drop across load resistor.

There are three major advantages of the vacuum-tube rectifier: (*a*) It is a stationary device that is simple in construction and not subject to the maintenance problems of rotary converters. (*b*) It rectifies independently of the frequency of the supply voltage and can be used on low-, high-, or variable-frequency circuits; the only limitation is imposed by the transit time of the electrons between the cathode and the anode. (*c*) It can deliver extremely high voltages, 100 kilovolts or higher, a feat impossible to achieve with rotating machinery because of commutation difficulties.

A basic rectifier circuit is shown in Fig. 2-8(*a*), and graphs of the transformer secondary voltage and the voltage across the load resistance versus time are given in Fig. 2-8(*b*). The circuit

can be used to rectify only one-half of each cycle; it is known as a *half-wave rectifier.*

Two half-wave rectifier tubes may be combined in a *full-wave* rectifier circuit, Fig. 2–9(*a*), where both portions of each cycle are converted to unidirectional pulsations, as shown in Fig. 2–9(*b*). We may assume that, as the polarity of the secondary winding of the supply transformer changes, the left-hand terminal connected to the anode of tube V_1 becomes positive with

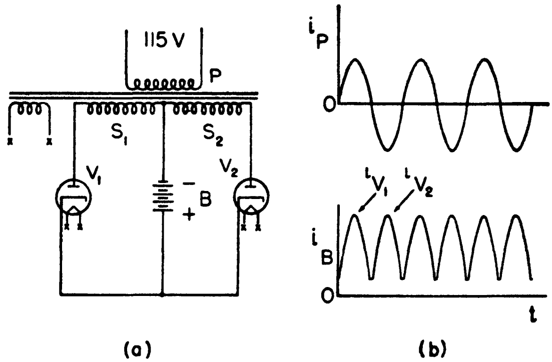


FIG. 2–9. (*a*) Two-tube full-wave rectifier circuit used in a storage-battery charger; (*b*) transformer primary current and composite load current supplied by both tubes.

respect to the center tap. The circuit is completed through the tube to the indirectly heated cathode and the load, which consists of the battery *B*. Tube V_1 conducts while tube V_2 remains inactive during this portion of the cycle because its anode is negative with respect to its cathode. On the reversal of the polarity, an instant later, tube V_2 conducts and tube V_1 becomes inactive. The conducting process repeats and alternates between the two tubes, being governed by the anode polarity.

In this circuit the cathodes of both tubes are connected to a common point that is the positive terminal of the load. This connection also permits the use of a tube made with two anodes and a common cathode, such as the one shown in Fig. 2–10. Circuits that incorporate tubes of this type will be discussed later.

A vacuum diode can withstand only a certain reversely applied maximum voltage, termed the *inverse peak voltage,* before conduction in the reverse direction or arc-back takes place through

the tube. The reverse current, if it occurs, is usually large and destructive. A rectifier tube is subjected to an inverse peak voltage that consists of the sum of the output voltage plus the applied reverse peak voltage. Highly evacuated tubes are generally used for service where the anode voltage is in excess of 5 kilovolts; frequently they are mounted in an oil-filled tank with the transformer.

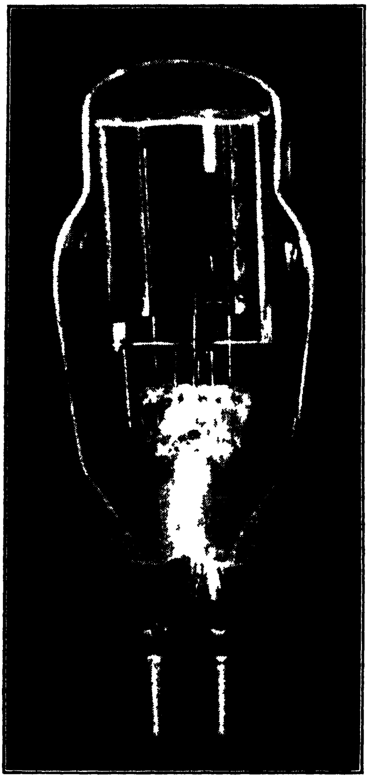


FIG. 2–10. Sectional view of a full-wave rectifier tube. *Courtesy Sylvania Electric Products, Inc.*

Bridge circuits, such as the one shown in Fig. 2–11, have been designed which use twice as many tubes, but each tube is subjected to an inverse peak voltage of only about one-half the value impressed on those in the circuit of Fig. 2–9(*a*).

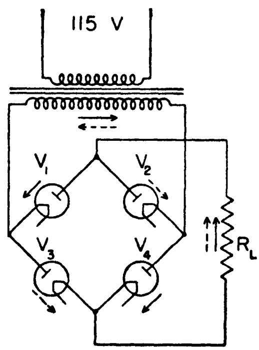


FIG. 2–11. Full-wave bridge-type rectifier circuit using four half-wave rectifier tubes.

Bridge rectifiers find application in multiphase circuits and are also used with the previously described dry-plate rectifiers.

2–8. Rectifier Filter Circuits

The d-c pulsations from a vacuum-tube rectifier cannot be used in some circuits without modification. Capacitors and inductors are circuit elements that have the ability to store and

subsequently release electrical energy; they are analogous to the mechanical equivalents of springs and flywheels. The energy W_C in joules stored in a capacitor is

$$W_C = \tfrac{1}{2}CE^2, \qquad (2\text{–}6)$$

where C is the capacitance in farads and E is the potential in volts.

Similarly, the energy W_L in joules stored in an inductor is

$$W_L = \tfrac{1}{2}LI^2, \qquad (2\text{–}7)$$

where L is the inductance in henries and I is the current in amperes.

Either a capacitance connected across the output terminals of a rectifier or an inductance connected in series with the load smooths the pulsations and makes the energy flow to the load more uniform. A circuit of this type, which often contains both of the elements and frequently in multiple sections, is known as a *filter circuit.*

In the full-wave rectifier circuit shown in Fig. 2–12, the negative output terminal and center tap of the transformer secondary

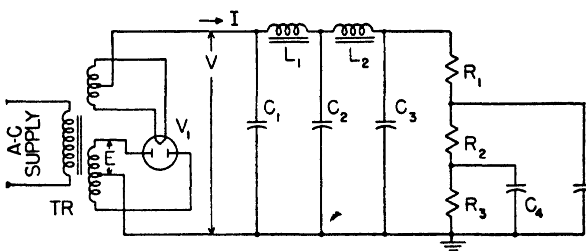


FIG. 2–12. Full-wave rectifier circuit with filter and voltage divider.

winding are grounded. The oscillograms given in Fig. 2–13 show the voltages between ground and the labeled points. As successive readings are taken toward the right, encompassing more filter elements, that is, nearer the load, the output voltage becomes smoother. If capacitor C_1 is used as shown, the filter is known as a *capacitor input* filter. The capacitor is charged to the peak voltage of the rectifier, and the maximum current required from the rectifier tube to charge the capacitor is large; it increases as the load increases. Consequently, the regulation, that is, the

variation of average output voltage with respect to load, is not particularly good.

When the capacitor C_1 is not used, the filter is known as a *choke input* filter. High-peak charging currents for capacitor C_2 are eliminated because the charging current must pass through inductor L_1, and this, in turn, results in lowered peak demands with a corresponding longer life of the rectifier tubes, lower output

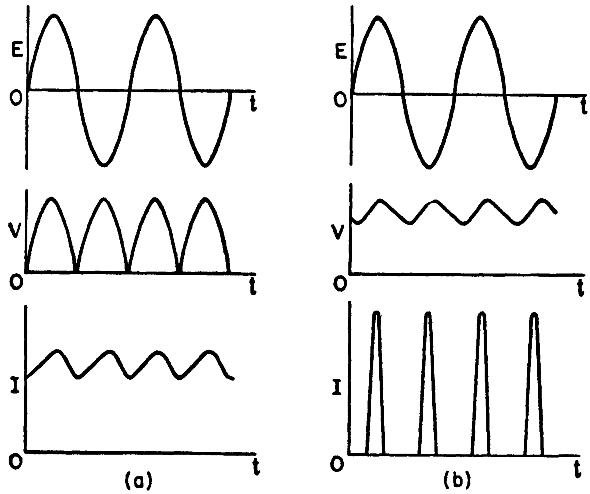


FIG. 2–13. Voltages and current in (*a*) choke-input filter circuit; (*b*) capacitor-input filter circuit.

voltage at the load terminals, and better regulation. The waveforms of voltage and current taken on a rectifier and filter with and without C_1 are shown in Fig. 2–13.

Often lower voltages are required in control circuits than are supplied at the output terminals of the rectifier. They may be obtained as shown in Fig. 2–12 by means of a *voltage divider,* consisting of two or more resistors in series or a tapped resistor connected across the rectifier or filter terminals. If the current requirement from any tap varies, auxiliary capacitors, such as C_4 or C_5, are used to keep the voltage constant. Electrolytic capacitors are commonly used on rectifier circuits that deliver less than 500 volts; they range in value from 4 to 40 microfarads. The inductors usually have values of about 30 henries and are often designed to serve additionally as field windings of electrodynamic loud-speakers in radio receiving circuits.

2–9. Voltage Multipliers

A circuit, consisting of two or more capacitors capable of being charged individually but so connected that the voltage across the combination is the sum of their voltages, is known as a *voltage-multiplier* circuit. For example, an average direct voltage of more than 220 volts can be obtained from a 110-volt a-c supply circuit without a transformer.

A voltage-doubler circuit, using two rectifier tubes, is shown in Fig. 2–14. Capacitors C_1 and C_2 are energy reservoirs; they

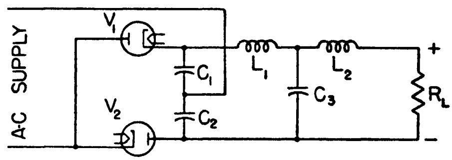


FIG. 2–14. Voltage-doubler circuit using two vacuum diodes.

are large since the voltage across each is quite low. Capacitor C_3 and inductors L_1 and L_2 constitute a simple T-type filter between the rectifier and the load R_L. When the upper wire of the a-c supply circuit is positive, C_2 is charged to the peak voltage of the source through V_2; when the polarity of the voltage reverses, that is, when the lower wire is positive, C_1 is charged through V_1. Polarities of the charged capacitors are such that the voltage across the two in series is about twice the peak value of the input voltage.

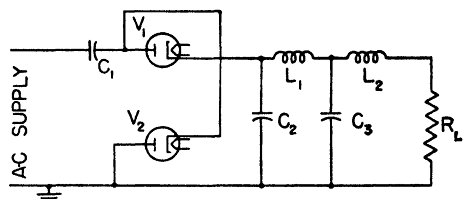


FIG. 2–15. Voltage-doubler circuit with negative terminal grounded.

Another voltage-doubler circuit, modified by grounding the negative terminal to the metal frame for safety and convenience in wiring, is shown in Fig. 2–15. Capacitor C_1 is charged to the peak voltage when the anode of V_2 is positive. During the following half cycle, C_2 is charged through V_1 to a voltage which

is the sum of the peak alternating voltage plus that across C_1, that is, about twice that on C_1. The filter and load portions of the circuit are similar to those in the previous circuit. Capacitor C_2 must have a voltage rating twice that of either C_1 or C_2 of Fig. 2–14 because the full output voltage exists across its terminals.

Voltage-tripler and voltage-quadrupler circuits are based on the same principle of alternately charging individual series-connected capacitors through rectifier tubes. Their use is limited; they find occasional application in low-current circuits.

2–10. Orientation by Induced Charges

Improved techniques, manufacturing methods, and materials have come about through the use of high direct voltages obtained from vacuum-tube rectifiers. Marked changes in electrical, mechanical, or optical characteristics are often induced in a material when the molecules are alined instead of being disposed chaotically.

We recall the simple physics experiment in which a glass rod, previously rubbed with silk to electrify it with a positive charge, is brought near a pith ball suspended on a silk fiber. The ball becomes electrified by induction. In accordance with Coulomb's law, Eq. 1–2, there is an attractive force between the charges, and the ball moves toward the rod. If the two touch, the pith ball gives up its induced, negative charge and is then repelled violently from the glass rod because of the remaining positive charge.

The manufacture of a specific sandpaper affords an interesting illustration of particle orientation. As shown in the simplified diagram, Fig. 2–16, a hopper feeds crushed rock, sand, or abrasive grains onto a traveling conveyor. These grains lie with their major axes in all possible directions. A strip of paper on which liquid glue has been spread moves with the conveyor into a drying oven. Within the oven, however, there are two electrically charged plates, one positive and the other negative, connected to a properly adjusted source of high voltage. As the grains of abrasive come within the field, the particles become electrified by induction; as each grain leaves the conveyor, it turns so that its major axis is parallel to the field and one end is imbedded in the glue. The glue dries while the grains of

abrasive remain in this position, and the product emerges from the oven ready to be cut into sheets. Under magnification the

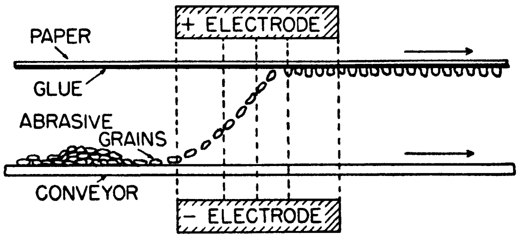


FIG. 2-16. Schematic diagram showing abrasive-grain orientation in manufacture of sandpaper.

sawlike cross section of sandpaper fabricated by this method appears as shown in Fig. 2-17. The manufacture of upholstering materials, whereby wool and other fibers are passed through,

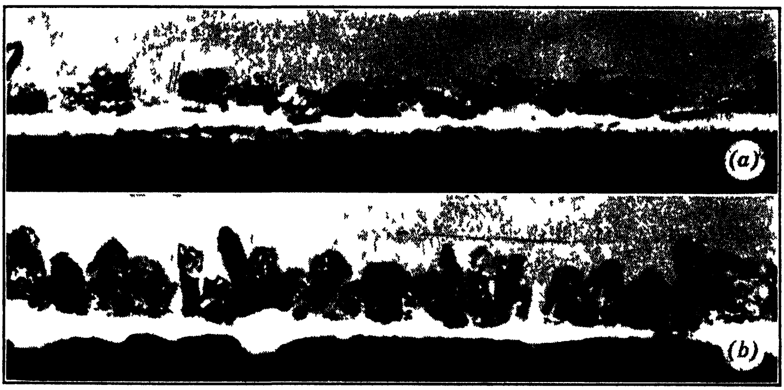


FIG 2-17 Magnified cross section showing abrasive grains in sandpaper. (a) Random displacement of grains; (b) electrically oriented grains. *Courtesy Behr-Manning Corporation.*

then glued or cemented within, the openings of large-meshed burlap while in an electric field, is another application of the same principle.

2-11. Electrical Detearing and Precipitation

After a metallic piece part is dipped in paint or lacquer, excess finishing material flows toward the bottom and tears form on the lower edges, as shown in Fig. 2-18(a). If allowed to

remain, they are unsightly and their presence often interferes with proper mechanical operation. To remedy this defect, an electric field, produced by a rectifier delivering approximately 80 kilovolts, is applied between a grounded hook that holds the newly dipped part while it is moving on a conveyor and passes over a wire grid. The finishing material is electrified by induction, and the excess particles are removed, as shown in Fig.

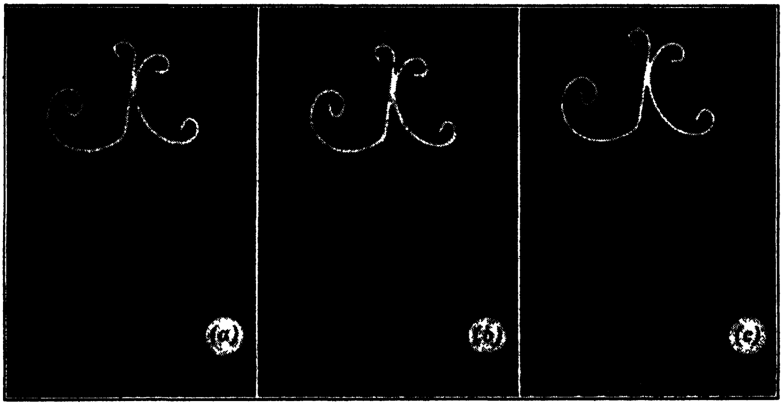
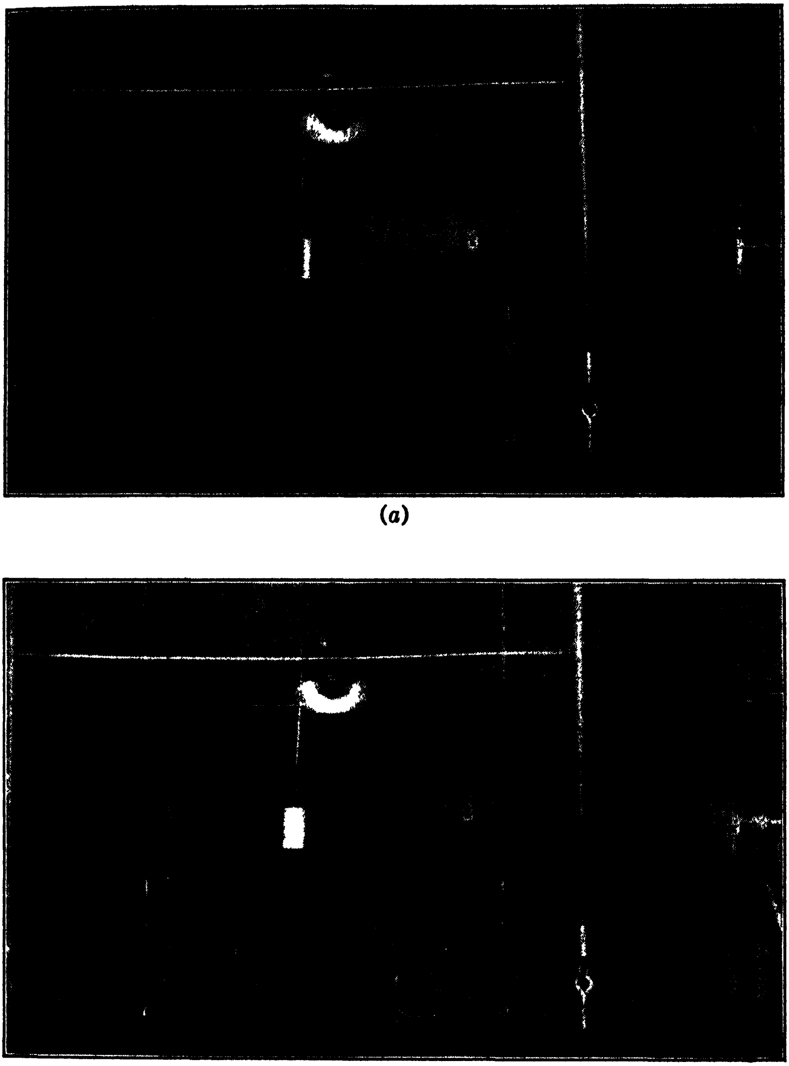


Fig. 2-18. Demonstration setup showing (*a*) dipped piece part with tears hung over grid; (*b*) energized grid pulling tears away by electrostatic attraction on induced charges in the tears; (*c*) deteared piece part with a uniform and smooth finish. *Courtesy Harper J. Ransburg Company.*

2-18(*b*), leaving the part uniformly coated, Fig. 2-18(*c*), and ready for drying.

One may visualize the repulsive forces between the lacquer particles and between them and the piece part by noting their paths as they move toward the charged grid. The voltage must be properly adjusted so that the coating is uniform for a given viscosity of finishing material, spacing of the part from the grid, and the desired speed through the detearing zone.

Paint or lacquer particles can also be ionized, and then they will be attracted and adhere to a metallic part which is to be coated, if it has an opposite polarity. The part is suspended from a grounded hook that is connected to one terminal of a high-voltage rectifier. Surrounding or alongside the path of the part, if it moves, are several ionizing wires; they are connected to the other terminal of the voltage supply. One or more spray



(a)

(b)

FIG. 2-19. (a) Cylinder being sprayed without electric field for 5 seconds with white paint atomized by spray gun; (b) same spray time and similar paint give a completely coated cylinder due to action of electric field. *Courtesy Harper J. Ransburg Company.*

guns direct the finishing material toward the piece part and past the ionizing wires where the individual particles become ionized, after which they are accelerated toward and adhere to the part, where each ion is neutralized. Any particles sprayed past the part are recalled by the attractive forces; that is, the piece part is also coated on the side opposite the spray gun.

In the demonstration setup, Fig. 2–19(*a*), a small cylindrical part was sprayed without a field for 5 seconds with white paint atomized by the spray gun at the right. The companion figure, Fig. 2–19(*b*), shows a similar part completely coated when sprayed under the same conditions and for the same interval of time but in an electric field. Electrostatic spraying makes possible a saving of 50 per cent or more of finishing materials and produces more uniform and consistent coatings. An installation where jacks, moving on a conveyor, are finished on passing through an electrostatic spray booth is illustrated in Fig. 2–20. The rectifier cabinet with its control panel is shown at the right.

During the manufacture of fluorescent lamps, phosphors are deposited within the tubes by utilizing the same basic principle. The method produces an exceptionally uniform coating and justifies its use by a gain of 3 to 4 per cent in light efficiency.

Electrostatic precipitation is not new; electrical means of removing smoke, dust, fly ash, acid mist, and other suspended particles were suggested more than a century ago and mechanical rectifiers were developed by Cottrell and others. Nevertheless, the simplicity and ease of application of the vacuum-tube rectifier adapt it for widespread use, in the interest of public health, not only for smoke abatement in industry but also in the vast untouched field of home air conditioning. Here applied electronics may well rival the pace set by electric refrigeration, which in less than 30 years has been developed, introduced in the home, and accepted as a household necessity.

In most commercial forms of precipitators, one electrode, commonly the negative, consists of a wire or rod of small diameter placed between larger, oppositely charged electrodes. When a high voltage is applied between the central conductor and ground, the central conductor becomes surrounded with a concentrated field of high potential gradient and a corona discharge. Gas passing between the electrodes becomes ionized and the suspended par-

ticles in the gas receive an electric charge. The charged particles are attracted to the oppositely charged electrode and adhere to its surface.

Large installations require potentials from 30 to 70 kilovolts to produce the corona discharge on the ionizer wire, but lower



Fig. 2-20. Automatic finishing of jacks by means of electrostatic spraying system. *Courtesy Walker Manufacturing Company.*

voltages suffice on the collector plates; they demand a current from 100 to 500 milliamperes at the high voltage. Three principal types of electrode designs have been developed. In the early pipe type, the gas is forced to flow through a nest of positively charged pipes. A negatively charged wire electrode is coaxial within each pipe and has a weight suspended at its lower end to keep it taut. Pipes measure from 6 to 9 inches in diameter and from 5 to 9 feet in length. The precipitated material collects on the smooth inside pipe surfaces and falls into a collecting hopper located below the pipes. In a later model, the

pipes are replaced by parallel plates, and the wires, suspended from an insulated support, are located between the plates. The latter are made of corrugated steel or wire screen; reinforced

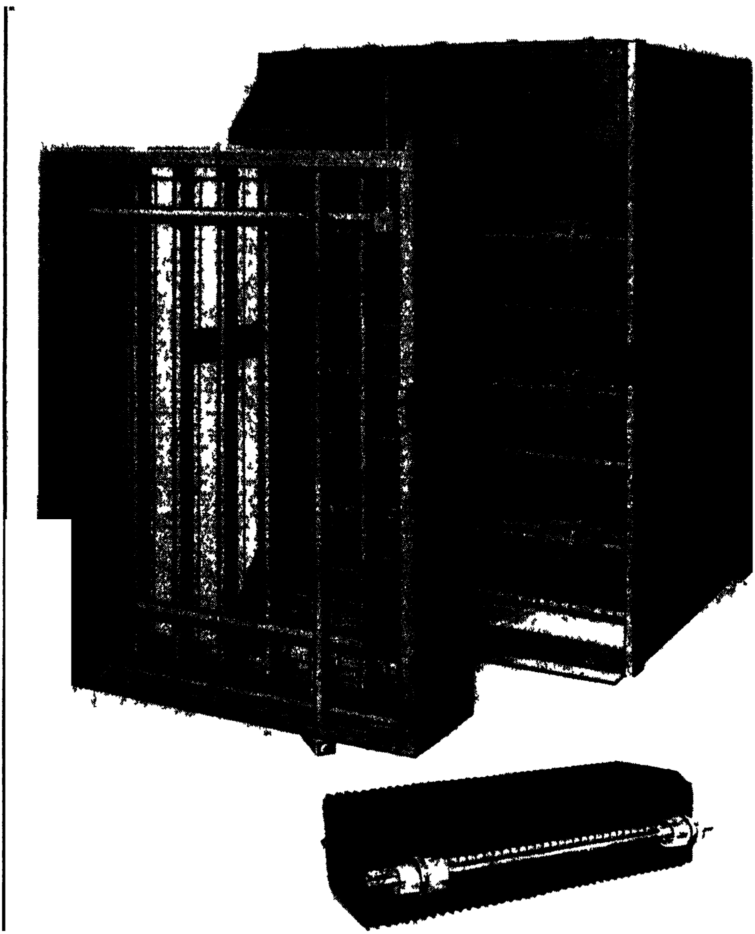


FIG. 2–21. Electronic air filter open to show ionizers and removable collector plate assemblies. *Courtesy American Air Filter Company, Inc.*

concrete is used frequently in very large installations. In a recent concentric-cylinder type, the inner finned, negatively charged cylinder produces the corona discharge; the precipitated

particles are deposited on the outer, positively charged cylinder and may either drop or be washed into a hopper.

Industrial cleaning cells are usually built into the ducts of an air-conditioning system and have capacities from 600 to 1800 cubic feet of gas or air per minute; their rating is established on a 90 per cent cleaning efficiency by a blackness test. A design in which the collector plates are in sections is shown in Fig. 2–21. These assemblies measure 2 to 3 feet in width and are made in standard units having a capacity of 1000 cubic feet of gas per minute per unit. The sections may be removed easily for inspection and cleaning.

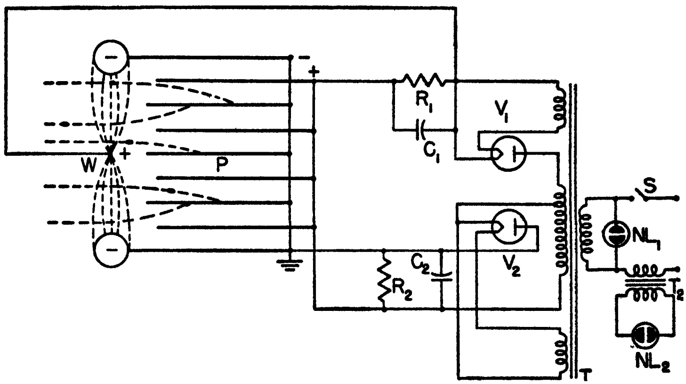


FIG. 2–22. Simplified circuit of an electronic precipitator.

Figure 2–22 gives the circuit of a unit with a capacity of 600 cubic feet of gas per minute, and Fig. 2–23 shows the mechanical arrangement of the power pack and other parts. The power pack contains a magnetic-leakage transformer T_1 which transforms the line voltage to 6 kilovolts. Two rectifier tubes, V_1 and V_2, that act as a voltage doubler, deliver approximately 6 kilovolts to the collector plates and 13 kilovolts to the ionizer wire. The very small diameter of the ionizer wire makes a relatively low ionizing voltage possible. Capacitors C_1 and C_2 provide filtering for the rectified voltage; resistors R_1 and R_2 act as safety and protective devices. When the circuit is disconnected, a time delay of at least 20 seconds exists before the thumb screws that hold the cover to the cells can be removed. During this time, capacitors C_1 and C_2 discharge through resistors R_1 and

R_2, respectively. The indicating transformer T_2, connected in series with the power transformer T_1, has a high reactance. A 1-watt neon lamp that indicates a short circuit is connected across

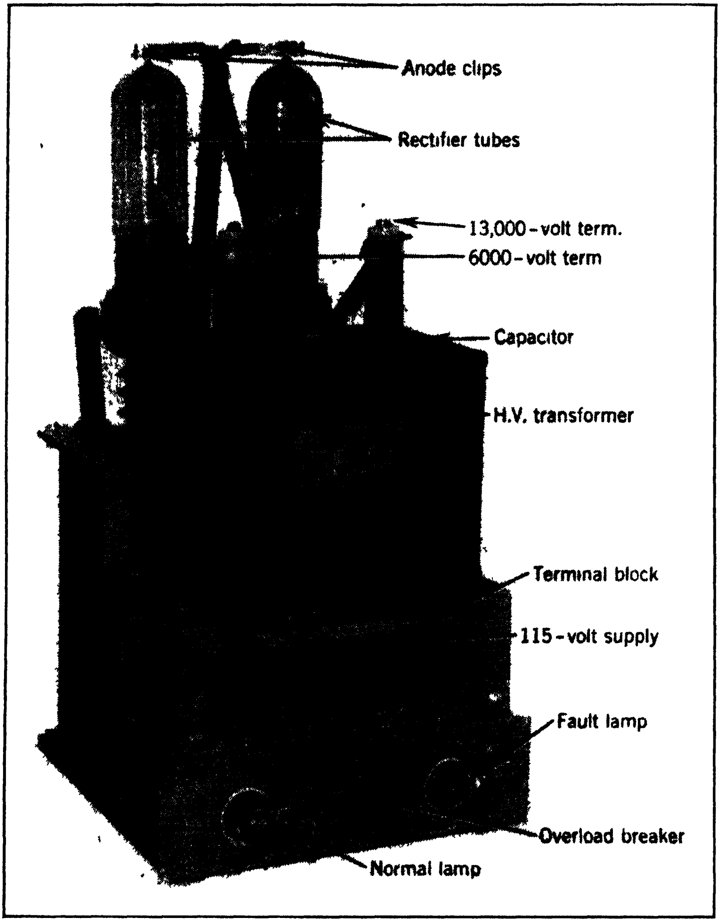


FIG. 2–23. Mechanical arrangement of the components within the power pack of an electronic precipitator. *Courtesy Westinghouse Electric Corporation.*

the secondary winding of T_2, and a similar lamp across the input glows when power is being supplied to the unit. The magnetic shunt within the power transformer provides protection against momentary overloads. A continued short circuit, however, such

as may be caused by a metallic bridge between the collector plates, lets practically all the supply voltage appear across the primary winding of T_2, with the result that the voltage across the primary winding of T_1 drops to a very low value; this insures that the tubes are operated at not much more than their normal current rating. The neon lamp provides a visual indication of overload, or a delayed action switch may be connected across the secondary winding of the indicating transformer to open the main supply circuit.

2–12. The Gaseous Diode

The space charge limits the anode current in a vacuum diode, and, therefore, the tube has a low current rating, the voltage drop across it is relatively large, and its regulation is poor. By the introduction of a gas or vapor, the space charge surrounding the cathode is partially neutralized by positive ions and the tube overcomes these limitations. During the manufacture of a gaseous diode, the tube is first evacuated and then a small quantity of argon or xenon is admitted to produce a low gas pressure or a few drops of mercury are inserted to provide a suitable vapor. Conduction is essentially the same as that described in the paragraphs on conduction through gases in Sec. 1–6, with the exception that the hot cathode emits a plentiful supply of electrons; this addition establishes and maintains an arc instead of a glow discharge. Positive ions neutralize the space charge of electrons around the cathode and allow comparatively large currents to flow to the anode. When the anode voltage of a gaseous tube reaches a value that may range from 10 to 30 volts, the gas ionizes and the anode current increases until it is limited only by the resistance in the anode circuit. The voltage drop across the tube remains nearly constant at a value close to the ionizing voltage irrespective of the magnitude of the load current, and consequently the efficiency and regulation of the tube are improved. Gas or vapor within a tube also reduces the maximum inverse voltage that may be applied to the tube, and this automatically confines the use of gaseous diodes to moderate-voltage high-current applications.

Hot-cathode gaseous diodes are made as high- or low-pressure tubes; both types are classified as phanotrons. The high-pressure diode, also known by the trade names Rectigon and Tungar,

has a low-voltage filament-type oxide-coated cathode and a carbon or graphite anode. The tube is filled with argon, xenon, or mercury vapor to a pressure of about 50 millimeters of mercury or more; this pressure serves the additional purpose of suppressing cathode evaporation, thereby permitting the cathode to be operated at a higher temperature. Diodes or rectifier tubes of this type, Fig. 2–24, have ratings up to 15 amperes; they find application in storage-battery chargers and also supply direct current for electroplating and other uses.



FIG. 2–24. Gaseous diode of the high-pressure mercury-vapor type. *Courtesy Continental Electric Company.*

The low-pressure diode is similar in construction to the high-pressure tube, but its gas or vapor pressure is much lower—only a few thousandths of a millimeter of mercury. Its greatest application lies in the supplying of moderate direct voltages and exciting current for generator and motor fields, magnetic chucks, and polarized reactors.

The efficiency of a gaseous diode depends on the voltage drop across the tube, and this, in turn, varies only slightly with the load; the voltage drop is more contingent on the kind of gas or vapor and on the operating temperature and gas pressure. Gaseous tubes should be installed in locations where the ambient temperature is reasonably constant. The electrodes in tubes filled with argon or xenon have a tendency to absorb the gas, and this results in tube failure. This problem does not arise with a mercury-vapor tube, but such a tube has a decidedly critical operating-temperature range outside of which the operation

becomes impaired because of the change in the temperature-sensitive vapor pressure.

Insufficient electron emission from the cathode causes positive-ion bombardment and destruction of that electrode. This occurs if the heater power is disconnected while the tube is being used or if inadequate time is allowed for the heater and cathode to come up to the operating temperature before the anode voltage is applied. It is particularly important to observe these precautions with large tubes; many of these require a heating time of several minutes before the proper operating temperature is obtained. The same basic rectifier circuits can be used with either vacuum or gaseous diodes.

Problems

1. What velocity in miles per hour must an electron reach in order that it can be emitted from a thoriated-tungsten cathode?

2. Plot the emission curve for tantalum according to Dushman's modification of Richardson's equation, using the constants given in Table 3. Indicate its place in the group of curves shown in Fig. 2–1.

3. A vacuum tube has 250 volts applied between the two parallel electrodes spaced 0.5 centimeter apart. If an electron is emitted and has zero velocity at the cathode, what will be its velocity in miles per hour when it reaches the anode? How much energy in watts will the electron transmit to the anode?

4. The cathode heater of the tube V_1 shown in Fig. 2–9 burns out during operation of the rectifier. List the effects of this on the load, on V_2, on the transformer, and on the magnitude of the supply current.

5. On the basis of Child's law, what is the diameter of a tungsten wire cathode which is mounted coaxially within a cylindrical anode spaced $\frac{1}{16}$ inch from the cathode and which emits a 10-milliampere current when the anode potential is 150 volts?

6. An inverted L-type filter is to be used between a full-wave rectifier and its load. The voltage across the capacitor, which has a value of 8 microfarads, is 250 volts, and the current through the load circuit is 150 milliamperes. What should be the value of the inductor portion of the filter in series with the load if the energy alternately stored in the inductor were to be equal to the energy stored in the capacitor? Does this energy interchange occur in practice?

7. Draw a simplified circuit diagram of a half-wave three-phase rectifier.

8. A three-phase half-wave rectifier supplies current to a resistance load. Plot a graph showing output current versus time for each phase and for the current in the load circuit. Repeat this for a three-phase full-wave rectifier.

9. In order to test the high voltage supplied to the ionizer wire of the precipitator shown in Fig. 2–22, a service man constructs a kilovoltmeter by

connecting a 1000-megohm 20-watt resistor in series with a d-c microammeter. The microammeter has a full-range scale of 200 microamperes and an internal resistance of 40 ohms. The meter scale is recalibrated to read 20 kilovolts. How much power is supplied to the kilovoltmeter when the pointer indicates 13 kilovolts?

10. A mercury-arc tube using a pool cathode, which requires no external heating power, operates at an anode supply voltage of 1500 volts. There is a voltage drop of 15 volts between the anode and the cathode. The load current is 5 amperes. What is the ratio of power input to power output, or the efficiency of the device?

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3.

The Vacuum Triode

The stream of electrons that flows between the cathode and the anode of a vacuum tube is no different from any other electric current. It is surrounded by a magnetic field and can be deflected magnetically by the same principle that moves an armature conductor in the magnetic field of an electric motor. The electrostatic control, proposed by Lee De Forest in 1907, is much simpler and more common. He interposed a gridlike wire mesh between the cathode and the anode. When a changing voltage was impressed between the grid and the cathode the resulting electric field increased or decreased, causing the anode current to decrease or increase correspondingly. This is one of the major discoveries of our time. It is responsible for the great advances in communication by wire and radio and has provided industry with a unique control device. Such a three-element high-vacuum tube is known as a *triode* or *pliotron*.

3–1. Grid Action and Construction

The grid of a triode is made by winding a fine nickel or alloy wire in a helix; each individual turn is subsequently welded to two supporting upright members. It is mounted so that it occupies a position between the cathode and the anode and completely surrounds the cathode. These electrodes and their assembly for a medium-sized power triode are illustrated in Fig. 3–1. Triodes are made in various designs, sizes, and ratings, depending on the service requirements. They range from large power tubes several feet long to the midget types less than 1 inch long. The tube shown in the figure is 9 inches long. High-power

triodes are sometimes made with multiple cathodes, grids, and anodes, each group connected in parallel, as illustrated in Fig. 3–2.

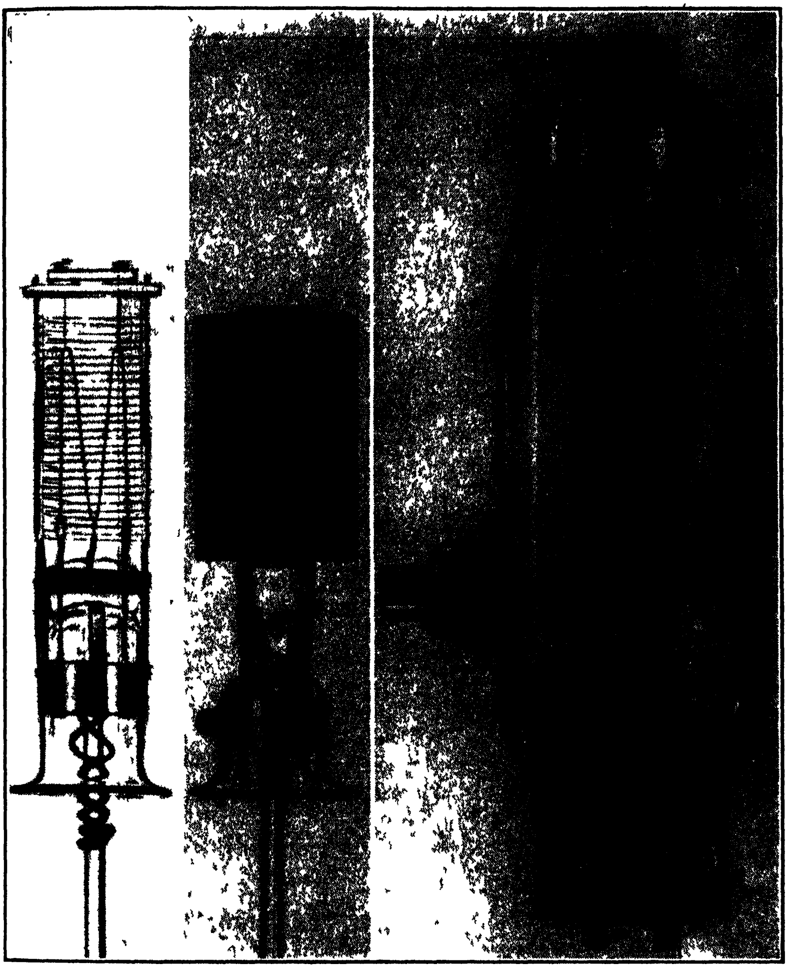


FIG. 3–1. Electrodes and complete assembly of a 200-watt power triode. Grid terminal on side, anode terminal on top, filament terminals in base. *Courtesy Taylor Tubes, Inc.*

This type of construction improves heat radiation and efficiency and increases life.

A voltage applied to the grid either aids or opposes the action of the anode voltage. Small changes in grid potential cause

large changes in anode current when the grid is located close to the cathode. Grid-wire diameter and grid-wire spacing, as well as grid placement, are design factors that affect the control action.



FIG. 3-2. Electrodes and complete assembly of a multiple-element power triode. *Courtesy Eitel McCullough, Inc.*

The behavior of a triode is analogous to that of the separately excited d-c generator where a small change in impressed voltage on the field winding produces a large change in the armature voltage and load current. The analogy is not complete; the

inductance of the field makes instantaneous field current changes impossible, and, at best, the field excitation requires appreciable energy.

When the grid of a vacuum triode is at zero potential with respect to the cathode, a definite anode current flows for a specified cathode temperature and anode potential. If a positive voltage is impressed on the grid, this electrode acts similarly to an anode and a current flows in the grid circuit. But, by making the grid negative with respect to the cathode, the grid current diminishes and the anode current is gradually reduced to zero as the grid potential assumes greater negative values; an increased negative grid potential transfers its effect into a decreased anode current. The mutual relationship between anode current and grid potential may

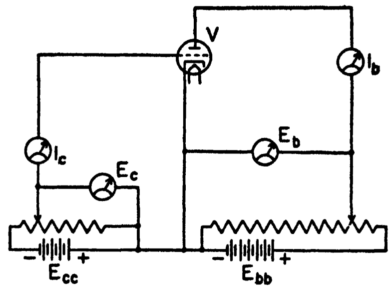


FIG. 3-3. Circuit for determining static characteristics of a triode.

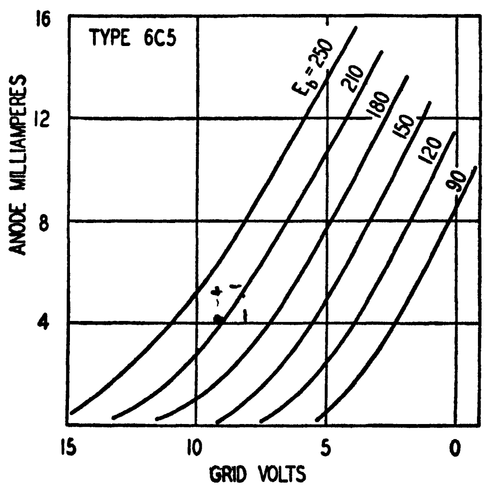


FIG. 3-4. Family of transfer characteristics of a triode.

be obtained by testing a tube in the circuit of Fig. 3-3 and plotting the data as a *transfer characteristic* like one of those shown in Fig. 3-4. The cathode temperature is held constant at

the rated heater voltage or current. A number of such curves plotted from data taken at various constant anode voltages comprise a family of transfer characteristics.

Data may also be obtained by keeping the grid potential constant and reading the anode current for various magnitudes of anode potential. These yield a family of *anode or plate characteristics* as shown in Fig. 3–5. Any given anode characteristic,

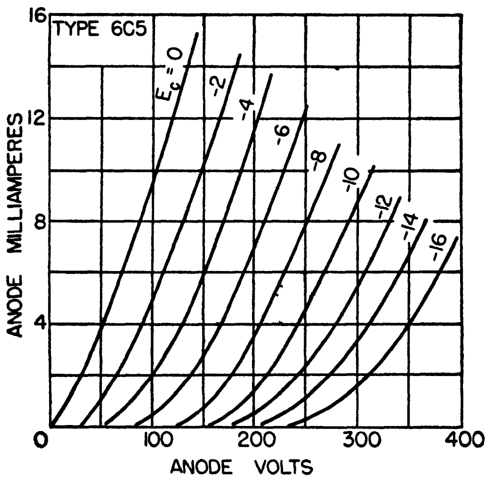


FIG. 3–5. Family of anode or plate characteristics of a triode.

or the entire family, may be plotted from the transfer characteristics by taking readings of anode currents and corresponding anode potentials on any fixed abscissa line, that is, at a certain grid potential.

The anode current for each curve of Fig. 3–4 reaches zero at a definite negative grid potential. The current is reduced to zero quite abruptly if the grid-wire spacing is uniform; nonuniform spacing results in a gradual reduction of the anode current to zero. Tubes of the latter type are termed *supercontrol* triodes.

3–2. Tube Factors

Expressions or factors that evaluate current and voltage interrelationships of a triode afford an index to tube behavior and allow comparisons to be made between tubes to determine their suitability for certain circuit functions. The three major tube

factors are the amplification factor, the tube resistance, and the transconductance of the tube.

An analysis of the curves of Fig. 3–4 shows that, if the grid potential is made more negative by an incremental value, the anode potential must be increased by a definite amount to maintain a constant anode current. The ratio of a small change in anode voltage to the required change in grid voltage, for a constant anode current, is termed the *amplification factor* and is designated by the letter μ. It is expressed by the equation

$$\mu = -\frac{\delta e_b}{\delta e_c} = -\frac{\Delta e_b}{\Delta e_c} \text{ approx.} \qquad (i_b \text{ constant}), \qquad (3\text{–}1)$$

where e_b and e_c are the instantaneous anode and grid voltages, respectively, and i_b is the instantaneous anode current. The steady anode voltage E_b, grid voltage E_c, and anode current I_b in the circuit of Fig. 3–3 are supplied by batteries. The derivative, Eq. 3–1, is in itself negative, and this makes the amplification factor μ positive. This factor may be determined approximately from readings or from the curves by taking increments of the two voltages Δe_b and Δe_c at a constant anode current. Since the curves for various anode voltages in Fig. 3–4 are not parallel, the amplification factor is not constant. Vacuum triodes are designed with amplification factors that range from about 3 to 150 or more.

In Sec. 1–2, resistance was defined as the ratio of voltage to current. In a triode, the *tube* or *plate resistance* r_p is the ratio of a small change in anode voltage to the resulting change in anode current with the grid potential held constant. The expression for the second tube factor is

$$r_p = \frac{\delta e_b}{\delta i_b} = \frac{\Delta e_b}{\Delta i_b} \text{ approx.} \qquad (e_c \text{ constant}). \qquad (3\text{–}2)$$

The relationship between voltage and current in Fig. 3–5 is not linear, and, therefore, the plate resistance of a triode is not obtained by dividing the total anode voltage by the total anode current; it must be evaluated at the operating point. Triodes are sometimes used as unilateral, nonlinear resistances. The slope at any point on a specific anode characteristic is the tube conductance at that point; it is the reciprocal of the tube resistance, that is, $g_p = 1/r_p$.

We obtain the third tube factor from the transfer characteristics, Fig. 3–4. The tangent at any operating point is the derivative of the anode current with respect to the grid potential with the anode voltage remaining constant. This factor is a conductance, and, since it is the ratio of a small change in current in one circuit to the corresponding change in voltage in

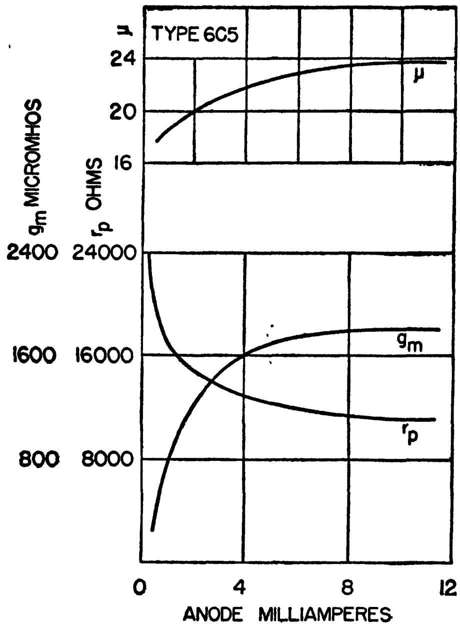


FIG. 3–6. Variation of tube factors with anode current.

another, it is termed *mutual conductance* or *transconductance.* It may be written as

$$g_m = \frac{\delta i_b}{\delta e_c} = \frac{\Delta i_b}{\Delta e_c} \quad \text{approx.} \qquad (e_b \text{ constant}), \qquad (3\text{–}3)$$

where g_m is the grid-anode transconductance and the other symbols retain their previously assigned designations.

The three tube factors are related. By combining Eqs. 3–1, 3–2, and 3–3 we derive the following equation

$$\mu = g_m r_p. \qquad (3\text{–}4)$$

The product of a conductance and resistance is a pure number; here it is the amplification factor. Transconductance is com-

monly expressed in micromhos or by its equivalent, microamperes per volt. If the transconductance of a tube is given in micromhos, the tube resistance must be expressed in megohms in order to obtain the amplification factor by means of Eq. 3–4. The variation in magnitude of the tube factors with respect to the anode current for a typical triode is given in Fig. 3–6.

3–3. Static and Dynamic Tube Characteristics

The tube characteristics shown in Figs. 3–4 and 3–5 were obtained with direct voltages and with no resistance load in the anode circuit to abstract energy. They are termed *static characteristics,* and those obtained with alternating voltages and with the anode current passing through an external load are called *dynamic characteristics.* If a current flows through the resistor in the anode circuit of Fig. 3–7, the energy $i_b{}^2R_L$, where i_b is the instantaneous total anode current and R_L is the resistance, is dissipated in the load resistor. The potential between the anode and the cathode will be less than the anode-battery voltage by the i_bR_L drop across the resistor, or

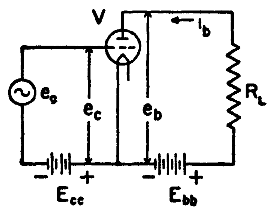


FIG. 3–7. Circuit of triode with a-c input and resistance load.

$$e_b = E_{bb} - i_bR_L. \tag{3–5}$$

The instantaneous total anode voltage e_b at any moment is a function of the anode current i_b, and this in turn depends on the instantaneous total grid voltage e_c. As the grid potential varies, shown by an alternating voltage superimposed on the steady grid potential in Fig. 3–7, the anode current i_b is altered, the voltage drop across the load resistor R_L changes, and, since the anode-battery voltage is fixed, the voltage between the anode and cathode also changes. A rise in anode current causes a rise in voltage drop across the load resistor and a corresponding decrease in anode voltage, and vice versa. This may be stated simply by saying that a variational voltage e_p and current i_p are superimposed on the steady anode voltage E_b and current I_b.

The dynamic anode characteristic may be obtained by inserting a resistor in the anode circuit of Fig. 3–3 and replotting the new

data or it may be constructed graphically by using the static anode characteristic as a foundation. One of the specific anode characteristics, previously shown in Fig. 3–5, is redrawn in Fig. 3–8. The graph of the linear equation, Eq. 3–5, known as a *load line,* is also drawn on the same sheet with the aid of the two intercepts of the line. These are (*a*) $i_b = 0$ when $e_b = E_{bb}$, and (*b*) $i_b = E_{bb}/R_L$ when $e_b = 0$.

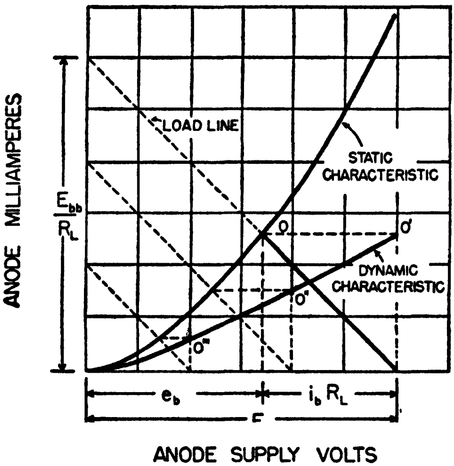


FIG. 3–8. Dynamic anode characteristic of a triode obtained from a static characteristic through the use of the load line.

The intersection of the static characteristic with the load line at the point O provides us with the value of the current i_b which flows through the resistor R_L under these conditions. This point is obtained when the supply voltage E_{bb} provides the anode-to-cathode voltage and is relocated by projecting it parallel with the voltage axis until it intersects a vertical line equal to the supply voltage. This fixes the point O'. New load lines for various magnitudes of supply voltage are drawn parallel to the original load line since the load resistance remains constant. These new load lines furnish additional points, such as O'' and O''', which comprise the dynamic anode characteristic. Even though the static characteristic is not linear, the dynamic anode characteristic may be made so, for all practical purposes, by a suitable choice of load resistance for a tube operating at a fixed anode supply voltage. Since the grid voltage did not enter into this construction,

the dynamic anode characteristic derivation applies equally well to the vacuum diode or kenotron; it shows that practically linear rectification, that is, a directly proportional relationship between incremental values of load current and applied voltage may be obtained if a proper load resistance is used.

By combining the static anode characteristics, a specific load line, and the static transfer characteristics, a resultant curve, shown in Fig. 3–9 and known as the dynamic transfer charac-

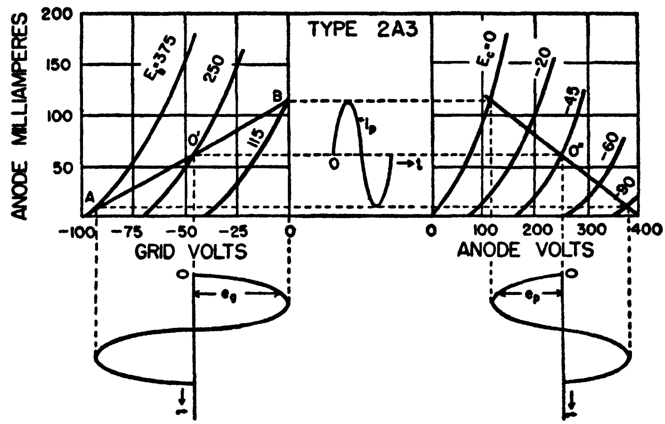


FIG. 3–9. Dynamic transfer characteristic derivation by graphical method.

teristic, may be constructed graphically. The approach toward linearity of response or faithful reproduction by converting a small varying grid voltage into a similarly varying anode current and a corresponding variational voltage across the load resistance is depicted in the figure. Anode characteristics are shown at the right and the load line for the given resistance load is drawn in place. For the tube indicated, we select the recommended operating point O'' at a grid voltage of -45 volts and an anode voltage of 250 volts. It is assumed that the grid potential may vary 45 volts on either side of the steady value; that is, the instantaneous total value may vary between 0 and -90 volts. This grid voltage variation results in an anode voltage that varies between 115 and 375 volts. The corresponding static transfer characteristics are next drawn at the left, and the operating point O', as well as other points of intersection of the anode characteristics with the load line, are projected to intersect the

proper valued transfer characteristic. A line drawn through the resultant points, such as A, O', and B, is the dynamic transfer characteristic.

If we assume that a sinusoidal alternating voltage e_g is impressed in the grid circuit of the tube, the corresponding variational alternating current i_p may be plotted by using the dynamic transfer characteristic as shown in the figure. The current i_p and the corresponding variational voltage e_p across the load resistance are not truly sinusoidal even with an optimum value of load resistance because the dynamic characteristic is not quite linear.

The deviation of waveform of the output from the input voltage may take the form of *amplitude distortion, frequency distortion, phase distortion,* or a combination of these. In practice a 5 per cent amplitude distortion is considered to be the upper limit. Distortion is of little interest in ordinary industrial applications, but it spells the difference between success and failure in telephone repeaters, in radio and television applications, in carrier-current installations that carry speech over power lines, and in electronic measurements.

The figure also discloses the important fact that the alternating output voltage across the load resistor is 180° out of phase with the alternating input voltage. This will be considered in detail later in this chapter.

3–4. Amplifier and Equivalent Circuit

It is desirable to use a triode with a high amplification factor in a voltage amplifier. On the other hand, a current amplifier, that is, one in which a large change in anode current results from a small change in grid voltage, requires a tube that has a high transconductance. Tubes used in power amplifiers usually have a low amplification factor and a low tube resistance. A simplified amplifier circuit is shown in Fig. 3–10, and the equivalent circuit in which the tube factors are assumed to be constant is given in Fig. 3–11.

The maximum voltage amplification of a circuit employing a triode may be calculated in the following manner. The sinusoidally varying grid voltage e_g is impressed across an extremely high resistance composed of the tube input resistance r_g. A high resistance R_g is connected across the input circuit to insure circuit

continuity for the steady grid voltage. The effect of e_g is shown as a generator with a voltage μe_g in the anode circuit. This

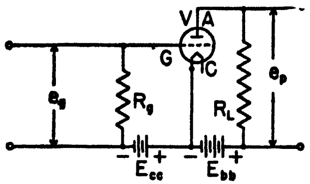


FIG. 3–10. Simplified circuit of an amplifier.

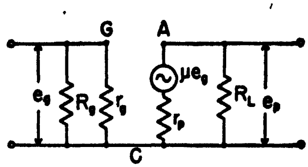


FIG. 3–11. Equivalent circuit of a simple amplifier.

voltage is divided across the tube resistance r_p and the load resistance R_L in proportion to their values, or

$$\mu e_g = i_p r_p + i_p R_L, \tag{3–6}$$

from which

$$i_p = \frac{\mu e_g}{r_p + R_L}. \tag{3–7}$$

But

$$e_p = i_p R_L, \tag{3–8}$$

and substituting the value of i_p from Eq. 3–7,

$$e_p = \frac{\mu e_g R_L}{r_p + R_L}. \tag{3–9}$$

The voltage amplification or gain of the tube is e_p/e_g, and, therefore, dividing Eq. 3–9 by e_g, we obtain

$$\frac{e_p}{e_g} = \frac{\mu R_L}{r_p + R_L} = \mu\left(1 - \frac{r_p}{r_p + R_L}\right). \tag{3–10}$$

Equation 3–10 shows that, as R_L increases, the value of the fraction decreases and the gain approaches μ, that is, the amplification factor of the tube, as a limit. Approximately 80 per cent of the tube amplification is realized when the load resistance is four times greater than the tube resistance. The direct voltage drop across a high load resistance, even for a small anode current, is quite large and necessitates the use of a high anode supply voltage in order to obtain the proper anode voltage.

The variational power output of a vacuum triode with a resistance load and for sinusoidal waveforms is the product of

the effective values of voltage and current. In terms of the maximum or peak values, the power P in watts is

$$P = E_p I_p = \frac{E_{pm} I_{pm}}{\sqrt{2}\sqrt{2}} = \frac{E_{pm} I_{pm}}{2}, \tag{3–11}$$

where E_p and I_p are the effective values, and E_{pm} and I_{pm} are the peak values, in volts and amperes of the variational voltage and current, respectively, in the anode circuit.

As in other electrical generators, the maximum power will be delivered to the load when the external or load resistance is equal

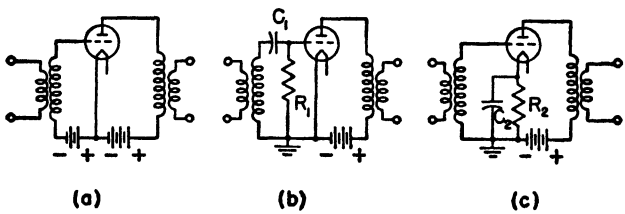


FIG. 3–12. Methods of obtaining steady grid potential. (*a*) Grid battery or fixed bias; (*b*) grid leak bias; (*c*) cathode bias.

to the internal or tube resistance. However, communication and motion picture amplifiers are usually designed to secure maximum undistorted power output; this is obtained when the load resistance is twice that of the tube resistance.

The circuit of Fig. 3–10 employs a battery, commonly known as a B battery, to supply the anode voltage. Battery power is generally used in instruments and portable applications, in which event the cathodes are of the filamentary type, supplied by an A battery, and the steady or d-c potential is obtained from a small grid-bias or C battery. Triodes operating on an a-c power supply usually have indirectly heated cathodes and the anode voltage is provided by a rectifier.

Three methods of obtaining a steady grid potential are in common use. A constant grid-bias voltage, whether obtained from a rectifier or a battery, as shown in Fig. 3–12(*a*), is termed a *fixed grid bias.*

The second method of obtaining a grid-biasing voltage, known as a *grid-leak bias,* Fig. 3–12(*b*), utilizes a small capacitor in series with the grid and a high resistance, termed a grid leak, between the grid and cathode. When an alternating voltage is

impressed on the input circuit, the grid becomes positive during one portion of the cycle and electrons from the cathode collect on the grid. The capacitor is charged and the grid assumes a negative potential. During the negative portion of the cycle, no grid current flows and the residual charge on the capacitor discharges only partially through the grid-leak resistor before the charging cycle repeats itself. This maintains the grid at a negative potential with respect to the cathode.

The third and most common method makes use of the *cathode bias*, Fig. 3–12(*c*). It is obtained by connecting a suitable resistor in series between the cathode and the negative or grounded terminal of the anode supply voltage. During tube operation, the anode current flows through the cathode resistor and produces a voltage drop across it. The junction of the resistor and cathode is positive with respect to the junction of the resistor and negative terminal of the anode battery or ground, and, therefore, the cathode is positive with respect to the grounded grid, or the grid is negative with respect to the cathode. A capacitor C_2 is connected in parallel with the resistor R_2 to provide a low-impedance path for the varying or alternating component of the anode current.

The electrodes within a vacuum triode form three capacitors, the grid-to-cathode, the anode-to-cathode, and the grid-to-anode capacitances. Their values depend on the size of the conductors and their separation. Even though they are very small, their reactances are low at extremely high frequencies and at these they readily conduct alternating currents. The grid-to-anode capacitance also transmits a portion of the high-frequency voltage variations, if any are present in the anode circuit, back to the grid circuit, causing distortion and oscillations under certain conditions. Special high-frequency tubes are made in which these interelectrode capacitances are minimized by reducing the size of the electrodes and eliminating tube bases and sockets.

3–5. Amplifier Operation and Coupling Circuits

If the grid voltage of a vacuum triode is adjusted so that it remains on the straight portion of the transfer characteristic during operation, the tube is termed a *class A amplifier*. In this application, the input impedance of the tube is high and practically no energy is required to control the output. With a

resistance load, the output waveform duplicates or closely approximates the input and the output current i_p varies linearly with the input voltage e_g, as was shown in Fig. 3–9. Since the steady anode current is high, the efficiency of the amplifier is low.

A tube is operated as a *class B amplifier* when its direct grid potential is so adjusted that the anode current just fails to flow. If an alternating signal voltage is applied in addition to this, current flows only during the time the grid has a less negative potential. The circuit shown in Fig. 3–13, known as a *push-pull amplifier,* is operated on this basis by using two tubes, each biased to the cutoff point. Either tube acts as an amplifier when its grid becomes less negative but remains inoperative when the grid potential increases to a more negative value. This is shown graphically in Fig. 3–14.

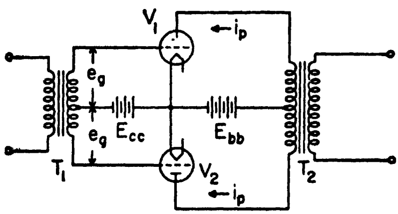


FIG. 3–13. Push-pull amplifier circuit.

The voltages applied to the grids are opposite in phase and the tubes operate alternately. Generally, a small portion of each tube characteristic is curved near the cutoff, and there the anode current to grid voltage relationship is not linear. Of course this causes distortion, but if the amplifier is operated with relatively large grid voltage variations the overall distortion still remains within acceptable limits.

Push-pull circuits are also commonly used with class A operated tubes as power amplifiers. An analysis of the circuit shows that magnetic saturation of the output transformer is avoided because the direct anode currents of the two tubes flow in opposite directions through the two halves of the primary winding and that variations in the anode supply voltage and even harmonics in the output voltage cancel out.

The third type, or *class C amplifier,* is one in which the grid bias is adjusted to be below the value required for anode current cutoff. As the grid voltage is caused to vary about this fixed position, anode current flows only when the grid potential becomes less negative than the cutoff value; that is, it flows during less than one-half of each cycle when an alternating grid

voltage is applied to the tube. The efficiency is greater than in either of the other two types. Class C amplifiers find application in oscillating circuits as will be shown later.

A single stage of amplification is seldom sufficient to amplify speech for reproduction or to close relays on the basis of a minute

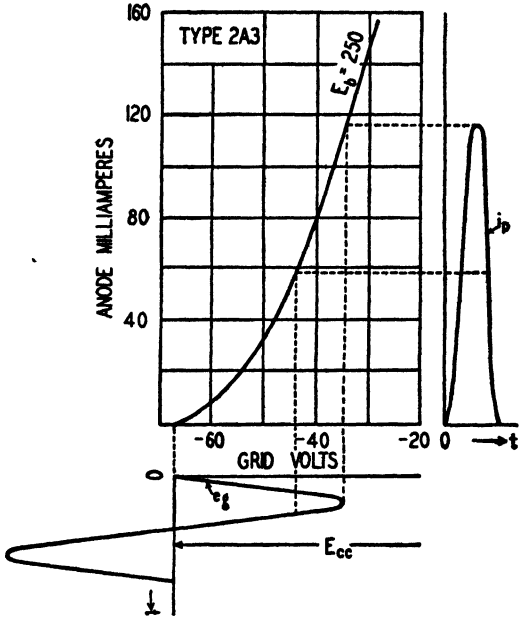


FIG. 3–14. Graphical analysis of anode-current variation in one of the tubes of a push-pull amplifier.

voltage change. Two or more stages are usually required; they are connected or coupled so that the output of one stage becomes the input of the next. There are three kinds of coupling: (*a*) resistance-capacitance coupling and its modification, impedance coupling; (*b*) transformer coupling; and (*c*) direct coupling.

Resistance-capacitance coupling is widely used because of its economy, compactness, and wide frequency response. In the typical circuit shown in Fig. 3–15(*a*), the anode resistor R_4 must have a high resistance value for high amplification. The decoupling circuit R_3C_3 is used in connection with the anode power supply; the capacitor C_3 provides a low reactance path for the a-c component of the anode current, permitting it to bypass the

power supply while the resistor R_3 acts as a series barrier to its flow. This refinement is used as an aid to more stable amplifier operation since the power pack supplies all stages. The input voltage is impressed across capacitor C_1 and the grid leak R_1 in series, and the grid is energized by that portion of the input voltage that appears across R_1. The response of an amplifier of this type is quite constant throughout the frequency range from about 150 to 10,000 cycles. Amplification drops off at the lower frequencies because of the loss in voltage across

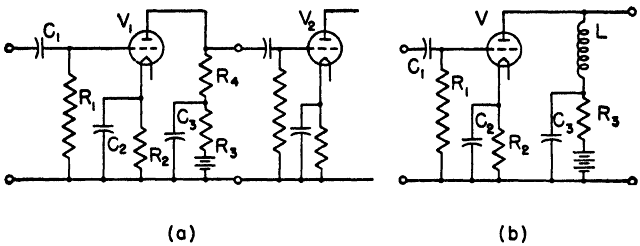


FIG. 3–15. (*a*) Resistance-capacitance-coupled amplifier; (*b*) impedance-coupled amplifier.

the coupling capacitor C_1 which has a reactance equal to $1/2\pi fC_1$ ohms. At high frequencies the shunting action of the anode-to-cathode capacitance, as well as the distributed capacitance of the wiring in the anode circuit, causes the amplification to be reduced. Special resonating circuits are added to extend the frequency range, that is, to produce video amplifiers, which amplify uniformly from about 100 to 5,000,000 cycles per second. These circuits are used in television and ultrahigh-frequency range finding.

Impedance coupling, Fig. 3–15(*b*), is a modification wherein the anode voltage is only slightly less than the anode supply voltage. This is achieved by replacing the load resistor R_4 with an inductor L that has a low d-c resistance. The inductive reactance, which varies directly as the frequency, is combined in quadrature with the resistance of the inductor to form the load impedance. This load impedance is high for the a-c component of the anode current. However, the load impedance is less for low than for high frequencies, and the amplifier response is not uniform but favors the higher frequencies. Shunting action of the distributed capacitance between wire turns and layers of the

inductor L also causes resonance and increased response in the upper portion of the frequency range. Except for this, the characteristic is similar to that of the resistance-capacitance-coupled amplifier.

Transformer coupling, Fig. 3–16(*a*), consists of the primary winding of a suitable transformer connected in the anode circuit of one tube and the secondary winding, which usually has a greater number of turns, in the grid circuit of the succeeding tube. The turns ratio N ranges from unity to about 3 to 1 or slightly

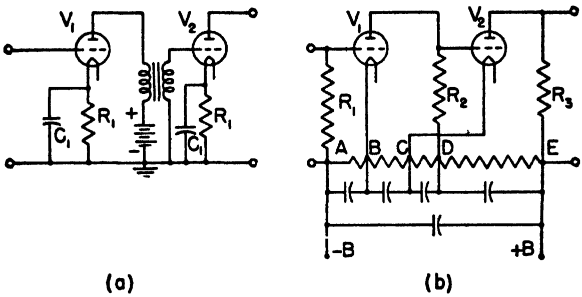


Fig. 3–16. (*a*) Transformer-coupled amplifier; (*b*) direct-coupled amplifier.

more. The coupling transformer acts as a voltage-amplifying device between the tubes, and, if the transformer primary winding reactance is large compared to the tube resistance, the amplification per stage is $N\mu$, where μ is the amplification factor of the tube. As in impedance coupling, the effects of distributed capacitance, resonance, and decreased load impedance at low frequencies tend to produce a nonuniform response curve. Transformer coupling is also used to couple a low-impedance source to a high-impedance load, and vice versa, in circuits that require a high or peaked response within a limited frequency range, and it also serves as a coupling device in push-pull amplifiers.

In *direct coupling,* used to amplify either or both direct and alternating voltages, the anode and grid circuits are connected directly with a metallic connection; the previous coupling methods isolate the direct anode voltage from the succeeding grid and permit only the alternating component of the output to be impressed on that grid. In one form of direct-coupled amplifier, shown in Fig. 3–16(*b*), the power supply is connected across a voltage divider AE. The grid circuit of the first tube V_1 returns through the grid resistor R_1 to the negative end A of the voltage

divider. The cathode of the tube is connected to a more positive point B, causing the grid to be negative with respect to the cathode by the amount of that voltage drop. The anode is connected through the load resistor R_2 to the point D on the voltage divider, which provides the proper anode voltage, and it is also directly connected to the grid of tube V_2. The cathode of tube V_2 is connected to the point C of the voltage divider. This point may be to the left of point D, as shown in the figure, because, for the proper grid bias for tube V_2, the current flowing through the load resistor R_2 and the corresponding voltage drop may cause that grid to be more negative than required. The anode of tube V_2 is connected through its load resistor R_3 to the most positive point E on the voltage divider. Capacitors are connected across the various points on the voltage divider to aid in voltage stabilization. When the amplifier is properly adjusted, the frequency response is uniform because frequency-discriminating devices, such as capacitors and inductors, are eliminated from the coupling between stages. At high frequencies, however, interelectrode and parasitic capacitances cause a reduction in the response characteristic.

3–6. Automatic Pilot

Amplifiers are utilized in control systems to maintain constant temperature, pressure, voltage, humidity, speed, or any other quantity that has a tendency to vary with outside causes or load changes. Any deviation from the desired value is detected by a conversion device, termed a *pickup* or *transducer*. For example, a change from the normal value may alter the resistance of a balanced Wheatstone bridge circuit; this produces a voltage that is amplified, and the amplifier output re-establishes the original condition by the operation of a power-activated device, such as a solenoid, valve, or motor. More specifically, the transducer may change the ratio arm resistances of a Wheatstone bridge through the aid of a wiper operating as an equivalent potentiometer. The readjusting device also carries a wiper, operating on a similar potentiometer, and causes corrective measures to be applied until both wipers are again in their central position. Output from a number of a-c resistance bridges may be connected in series, and the resultant unbalanced voltage, if deviation from normal occurs, may be applied to the input of a

single amplifier. In electronic control systems, as in others, overcontrol, hunting, and lag must be minimized or, preferably, eliminated.

The automatic pilot, which offers an interesting application of the vacuum triode as an amplifier and control device, was developed to keep an airplane on a straight and level flight in a

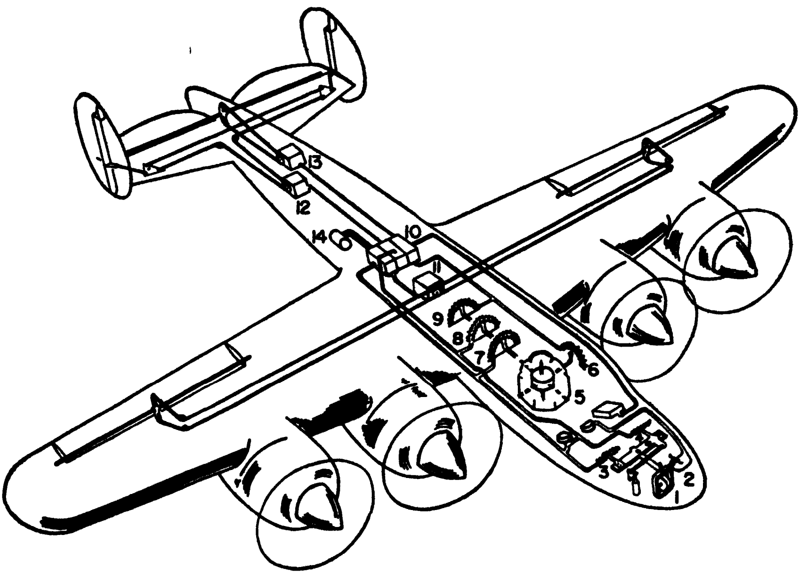


FIG. 3–17. Simplified schematic diagram of automatic pilot and components in airplane. Actual location of parts differs from that in figure. *Courtesy Minneapolis-Honeywell Regulator Company.*

predetermined direction. Control of an airplane can be resolved about three perpendicular axes: (*a*) the roll axis controlled by the ailerons, (*b*) the pitch axis controlled by the elevator, and (*c*) the turn axis controlled by the rudder. In making a turn the plane is made to roll by operating the ailerons. At the proper angle of bank, the ailerons are streamlined until the turn has been made, after which they are displaced in the opposite direction until the plane returns to level flight. The rudder and elevator control surfaces must operate simultaneously in a similar manner in order to effect a properly operated turn.

The automatic pilot is shown schematically simplified in Fig. 3–17. A gyroscopically operated directional stabilizer 1, which remains fixed in space, detects any airplane roll, turn, or both.

The rotor remains in a horizontal position together with a wiper 2 which is mounted in a fixed position with respect to the rotor. The potentiometer windings 3 in the aileron circuit and 4 in the rudder circuit are attached to the gyroscope case which is rigidly fastened to the plane. A similar but vertically operated gyroscope 5 detects vertical axis deviations and, through an unbalance of the elevator potentiometer 6, deviation from horizontal flight. If roll occurs, the gyroscope operates the aileron potentiometer 7, the skid potentiometer 8, and the elevator potentiometer 9. These unbalances are transmitted as voltages to their respective channels of the three-section amplifier 10, which in turn causes the operation of the correcting motors 11 for aileron control, 12 for rudder control, and 13 for elevator control until each potentiometer wiper is again centrally located. A rotary inverter 14 supplies alternating current for the operation of the system.

A simplified circuit, consisting of a composite bridge circuit, a two-stage resistance-capacitance-coupled amplifier supplied by a full-wave rectifier, and a vacuum-tube discriminator with relays, used for aileron control, is shown in Fig. 3–18. Any roll axis deviation or any turn of the airplane introduces voltages from potentiometers 3 and 7 in series to the amplifier input circuit. The manual turn control is used by the pilot for making properly coordinated turns. Circuit refinements in the bridge circuits allow manual adjustments to be made for normal straight and level flight and provide proper coordinated effort between aileron and rudder control.

The amplifier and control tubes V_{1a} and V_{1b} are shown as separate tubes but in reality they are mounted in one envelope and comprise the two sections of a twin triode. Another twin triode, a discriminator tube V_2, senses the direction in which corrective measures must be applied by the relative polarity of the signal voltage impressed on the discriminator tube by the control tube V_{1b}. A full-wave rectifier V_3 supplies anode voltages for the amplifier tube V_{1a} and the control tube V_{1b} and also supplies the grid biases for tubes V_{1b} and V_2. The cathodes are energized with direct current from a battery. A bridge transformer T_1 supplies an alternating voltage to the various bridge circuits, and a power transformer T_2 provides the high voltages for the rectifier and discriminator tubes.

Through manual operation or by airplane deviation from a given course, an alternating unbalance or signal voltage, having a magnitude depending on the amount of deviation, is applied to the grid of the amplifier tube V_{1a}. This voltage is either in phase or 180° out of phase with the supply voltage, depending on whether the displacement of the wiper is to the right or left of the central position. There is no constant or fixed grid bias on

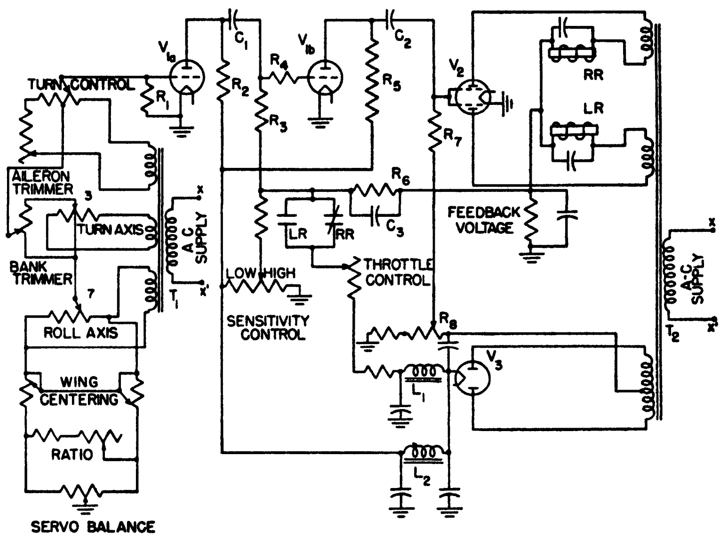


FIG. 3–18. Simplified circuit of aileron control portion of automatic pilot. *Courtesy Minneapolis-Honeywell Regulator Company.*

tube V_{1a}; however, a grid leak R_1 keeps the tube in a stable operating condition in the event that a momentary open circuit should occur at any potentiometer. The anode current of V_{1a} rises and falls on the linear portion of the anode characteristic, and the changing anode voltage across the load resistor R_2 is impressed through the coupling capacitor C_1 and the series resistor R_4 on the grid of V_{1b}. Resistor R_4 limits the current in the grid circuit of V_{1b} during the positive portions of the impressed signal voltage. Its grid is biased through the resistor R_3 by a voltage from the sensitivity, throttle control, and feedback sources. The anode current of V_{1b} is normally held at the saturation point; it is reduced by a signal of negative polarity but cannot be increased by a signal of positive polarity. The sensi-

tivity control, when moved toward a more positive grid bias, shifts the operating point to the right on the anode-current grid-voltage characteristic, and, consequently, a greater negative signal is required to produce any anode current reduction. The feedback voltage is used to increase the sensitivity of the tube to weak signals, causing firm and positive relay action. The throttle control bias, consisting of a larger positive voltage derived from the rectifier power supply through the upper filter choke L_1, is applied after either inner pair of contacts on relay *RR* or *LR* is closed. The anode current varies intermittently with the amplitude of the input signal and, therefore, through the control of the bias on V_{1b}, causes the motor and the associated servo balance potentiometer to reach its central position by means of longer or shorter steps. The time-delay circuit R_6C_3 acts in conjunction with this control to bias the grid for a short interval of time after the relay contacts open.

The discriminator tube V_2 consists of a twin triode with its cathodes grounded and the grids tied together and biased through the grid leak R_7 from the variable control R_8 located in the rectifier ground-return circuit. A relay is connected in each anode circuit as a load, and transformer secondary windings supply the anode potentials. The polarity of each anode is alternately positive and negative, but at any given instant the phase displacement of one is 180° out of phase with respect to the other. Either tube section functions only when its anode is positive. Since the power and the bridge transformers are connected to the same source of supply, and since no phase shifting except for the inherent 180° or phase reversal exists in the amplifier and control circuit, a positive alternation of voltage on the grids of V_2 can result in current through the right relay *RR* only if the upper anode of V_2 is positive. At that same instant the lower anode is negative and no current flows in the left relay *LR*. When the input signal through C_2 reverses, the half cycle that makes both grids negative causes no anode current to flow in either section of V_2. The capacitor connected across the relay winding was charged during the previous pulse and holds the relay closed between pulses. If the input signal reverses in phase, as occurs when the bridge arms become unbalanced in the opposite direction, the positive half cycle impressed on the grids of V_2 causes current to flow in the lower circuit, and the

left relay *LR* is energized because the anode in that circuit is positive at that instant. The contacts on the right relay connected in the motor circuit cause operation in one direction; those on the left relay cause movement in the opposite direction.

There are only ten tubes in the complete amplifier, nine of which are in the three amplifier, control, and discriminator stages for aileron, rudder, and elevator control. One rectifier tube supplies the d-c requirements.

3-7. Vacuum Triode as Oscillator

The power output of a triode is, of course, much greater than the input, and, by feeding a portion of the output back to the

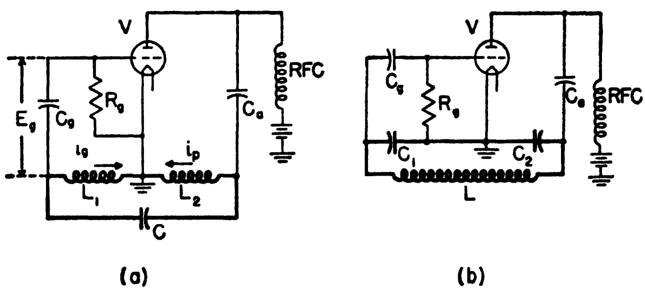


FIG. 3-19. Simple oscillator circuits. (*a*) Hartley oscillator; (*b*) Colpitts oscillator. Tank circuits are drawn in heavy lines.

grid circuit in the proper phase relationship, the output power can be increased tremendously. This process is termed *regeneration*. Feedback may be achieved either by capacitive or inductive coupling. Adjustment for maximum amplification is critical, and, if the feedback voltage is increased too much, the triode produces self-sustaining oscillations, that is, an alternating voltage, which may range from a few cycles to many megacycles per second, depending on the anode-circuit constants of capacitance and inductance, commonly called the *tank circuit*. Since oscillators are static devices that convert d-c from the anode power supply into a-c power output throughout such a wide frequency range, they are a very important addition to electronic equipment.

Many oscillator circuits have been developed, of which the Hartley and Colpitts circuits, shown in Figs. 3-19(*a*) and (*b*), respectively, are typical. In the illustrations of both these circuits the tank or energy-storage circuits, are drawn in heavy lines;

in the Hartley oscillator the tank circuit consists of two inductors L_1 and L_2 in series with the capacitor C, while in the Colpitts circuit these elements are interchanged. Both circuits use a low-resistance high-impedance inductor RFC, commonly termed a radio-frequency choke, to prevent the high-frequency current from passing through the power supply, and they both have a low-impedance capacitor C_a that permits the passage of a periodic pulse to the tank circuit. Each circuit uses a grid capacitor C_g and a grid leak R_g to provide a negative grid bias during operation.

It may be assumed that mutual inductance exists between the two tank-circuit inductors of the Hartley oscillator, but this is not essential since feedback also occurs through the capacitor C. Capacitors C_a, C, and C_g are connected in series between the anode and cathode; capacitors C_a, C_2, C_1, and C_g serve the similar purpose for feedback in the Colpitts circuit.

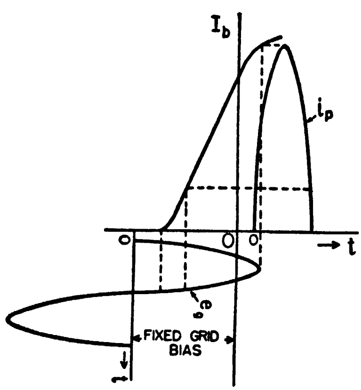


FIG. 3–20. Graphical analysis of a triode operating as a class C amplifier or oscillator.

At the instant when the Hartley circuit is connected to the anode power supply, the grid voltage e_g is zero and a current i_b flows in the anode circuit. A current pulse also flows from the anode terminal through C_a and L_2 to the ground or negative terminal of the power supply. This pulse induces in L_1 a voltage, which continues as long as the current increases, and gives the grid a positive potential with respect to the cathode, causing increased anode current. The grid attracts electrons, and the grid capacitor by becoming charged gives the grid a negative bias. As long as the pulse lasts, the induced voltage and the anode current continue to rise until the anode current is limited by the increased grid bias. During this time the capacitor C is charged but it then discharges through the inductor; opposite-phase voltages are induced in L_2 and L_1, causing the grid to assume an increasing negative bias; and the anode current is reduced to zero, as shown in Fig. 3–20. The current in the tank-circuit inductor,

however, continues to flow until the electrostatic energy stored in capacitor C is transformed to electromagnetic energy surrounding inductors L_1 and L_2. In the meantime the grid is biased beyond the cutoff value. The tank capacitor again becomes charged and the cycle of operations is repeated. Of course the starting transient may be spread over several cycles, but after that a current pulse is delivered to the tank circuit during every cycle of alternating current that flows in that circuit. The approximate frequency f in cycles per second of the oscillator is given by the equation

$$f = \frac{1}{2\pi \sqrt{LC}}, \tag{3-12}$$

where L is the combined inductance in henries of inductors L_1 and L_2, and C is the capacitance in farads of the tank capacitor.

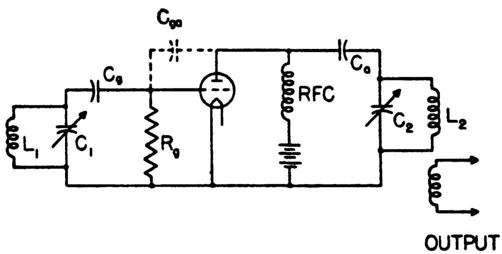


FIG. 3-21. Tuned-anode tuned-grid oscillator circuit.

The action of a pallet, escapement, and pendulum forms an interesting mechanical analogy to an oscillator.

Energy is abstracted from the tank circuit by either inductive or capacitive coupling. A fixed grid bias or cathode bias may be used in oscillator circuits, but the grid-leak type is preferred because it is self-adjusting for various load conditions and is required if the oscillator is to be self-starting.

Other oscillator circuits, such as the tuned-grid tuned-anode, push-pull, and electron-coupled types, have been developed; the kind of duty, nature of application, and cost usually determine the adopted design. The grid-to-anode interelectrode capacitance acts as the coupling means in the tuned-grid tuned-anode type of oscillator, Fig. 3-21. The tube capacitance C_{ga}, shown in dotted lines, is in series with the grid capacitor C_g and the anode capacitor C_a, both of which are comparatively large, and,

consequently, it behaves as though it were connected across the top terminals of capacitors C_1 and C_2. This interelectrode capacitance permits a feedback voltage to be impressed on the grid similar to the action in a Colpitts oscillator; it accounts for the instability of high-gain tuned-circuit amplifiers. Tubes may be connected in parallel for a greater power output, but if only two tubes are used the push-pull type of oscillator is preferred because it tends to produce an output voltage of purer waveform.

3-8. Oscillator Relay Control

It is axiomatic in a control apparatus that a measurable change must occur before a correction can be applied. In the simplest type, the measuring device may have the moving element equipped with electrical contacts that close circuit connections to instigate suitable control operations. A different approach to similar control problems is through the use of the oscillator relay shown in Fig. 3-22.

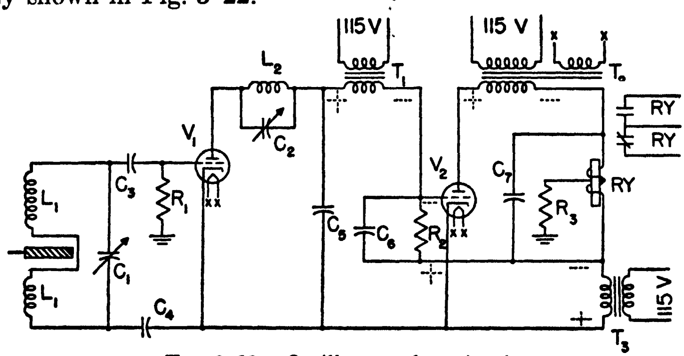


FIG. 3-22. Oscillator relay circuit.

The tuned-anode tuned-grid oscillator tube V_1 and the direct-coupled amplifier tube V_2 are separate sections of a twin triode. The heaters are energized from a low-voltage secondary winding x-x on transformer T_2, and both anodes are connected to a source of alternating voltage supplied by the transformers T_1 and T_2. When the oscillator anode circuit L_2, C_2 and the grid circuit L_1, C_1 are in resonance, oscillations are produced during each positive alternation of the anode supply voltage due to the coupling of the interelectrode capacitance between the grid and the anode. The operating frequency, which in one case is about 15 megacycles, is obtained by suitable design of inductors

L_1 and L_2 and the adjustment of the variable capacitors C_1 and C_2.

As shown in Fig. 3–23, the inductor L_1 consists of two parts so arranged that a small aluminum vane mounted on a meter movement, when passing between the parts, either resonates or deresonates the grid circuit with respect to the anode circuit, depending on the original adjustment. The inductance of L_1 is reduced when the vane comes near or passes between the portions of the inductor. Capacitors C_3 and C_4 isolate the tuned-grid circuit, and the combination acts as a grid capacitor. The grid leak is R_1. Capacitor C_5, which completes the high-frequency circuit to the cathode, permits the oscillations to bypass the anode-supply transformer T_1. The oscillator grid circuit is completed through R_1, the ground, a biasing resistor R_3, a tap on the relay where regeneration is introduced, and finally through a biasing-potential transformer T_3 to the cathode.

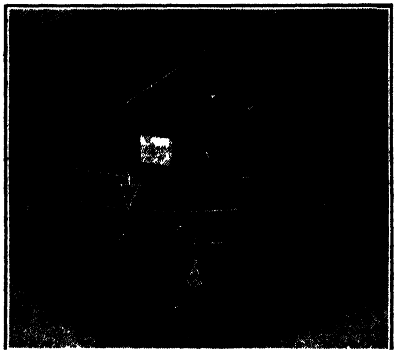


FIG. 3–23. Oscillator relay actuating mechanism. The position of the split inductor *A* is preset to the position indicated by pointer *B*. Vane *C* is attached to indicating pointer. *Courtesy Wheelco Instruments Company.*

The steady component of the anode current resulting from the grid-leak bias flows through the anode coupling and load resistor R_2, and since that current is always greater than zero, a compensating or opposite polarity voltage, equal to the normal voltage drop across the load resistor when the tube oscillates and minimum current flows, is introduced into the circuit by T_3. The net bias voltage on the amplifier is, therefore, zero during the operative, positive portions of the applied alternating voltage, and the anode current through V_2 is quite large. The relay is energized during this portion of the cycle and the shunting capacitor C_7 is charged. During the negative portion of the voltage cycle, the capacitor discharges through the relay and prevents armature chatter.

If the vane is introduced in L_1, the input circuit of the oscillator V_1 is deresonated, oscillations cease, the grid bias decreases, and the steady anode current increases greatly. The correspondingly increased voltage drop across the load resistor R_2 is no longer balanced out by the voltage from T_3, and the bias of the amplifier tube V_2 becomes more negative, causing the amplifier anode current to decrease. The lowered current in the relay, in turn, removes that portion of the positive potential on the cathode of V_1 which is due to the reduced voltage across the lower section of the relay, with the result that the oscillator bias is decreased still more or the action is regenerative. As a consequence, the relay is de-energized and initiates control operations.

Oscillator relay mechanisms have been made in which a 0.0001-inch movement of a vane having the dimensions 0.750 inch by 0.375 inch by 0.002 inch, mounted on a meter element, caused a change of 20 milliamperes in the anode circuit, that is, a change from zero to the maximum anode current. Similar adaptations of this principle are made in railway signaling systems, where locomotives carry the oscillator, and in the leveling of elevator cars. The movable vane in the latter case is attached to the elevator and passes between two portions of the grid inductor or between the grid and the anode inductors, if these are magnetically coupled, causing cessation of oscillations with relay and brake operation. By these means an elevator floor can be made to stop within the range of $\frac{1}{8}$ inch of the dead level position. An auxiliary circuit under control of the operator permits the elevator to stop only at the desired floors.

The circuit of Fig. 3–22 can be adapted to act as a materials level-sensing and control mechanism by modifying the grid circuit of the oscillator so that the capacitor C_1 becomes the variable element. The storage tank containing the liquid may be a portion of a reserve storage system, such as is used in the petroleum industry, or it may be a part of a processing plant where liquid levels vary constantly. Two general types of variable level-sensing capacitors have been developed: (*a*) the manometric type, which consists of a metal cylinder surrounding a glass or plastic tube in which the conducting liquid rises and falls; and (*b*) the immersion type, in which one capacitor element is mounted within a nonmetallic tube acting as a dielectric and so arranged that the liquid rises and falls outside the tube.

The capacitance C in microfarads of an air-dielectric capacitor, consisting of two parallel plates, is given by the formula

$$C = 8.85 \times 10^{-8} \frac{Ak}{D}, \tag{3-13}$$

where A is the area of one side of one of the plates in square centimeters, k is the dielectric constant (approximately 1), and D is the distance in centimeters between the plates.

If the air dielectric in the capacitor is replaced by a different dielectric having a constant k', the capacity increases by the ratio of k'/k. If the material between the plates is a conductor, insulating films are placed on the plates. Neglecting fringe effects, as was done in Eq. 3-13, the capacitance in microfarads is expressed by

$$C_1 = 8.85 \times 10^{-8} \frac{Ak'}{D_1 + D_2}, \tag{3-14}$$

where k' is the dielectric constant of the insulating film, and D_1 and D_2 are the thicknesses in centimeters of the films on the two plates. When the conducting medium rises between the plates, the capacitance varies directly as the height of the liquid and increases in direct proportion as the dielectric constant changes from air to that of the dielectric constant of the insulating films.

3-9. Carrier-current Applications

If the tank circuit of an oscillator is coupled to a fixed output circuit, only alternating current of a constant amplitude, often termed a *carrier* current, flows in that circuit. By making the frequency sufficiently high and by using a resonant output circuit consisting of an inductor and an antenna, the antenna acting as a capacitor, electromagnetic energy is radiated. The high-frequency carrier current may be interrupted by keying according to a predetermined code, and we have a radiotelegraph transmitter. The receiver, which also uses an antenna as a capacitor in a tuned circuit, has the incoming signal voltage impressed on an amplifier. A separate constant-amplitude alternating voltage, supplied by a variable-frequency low-power vacuum-tube oscillator, is coupled to the amplifier output circuit. The composite output current contains the frequencies of both the received and local oscillators as well as their sum and difference frequencies.

If the frequency of the local oscillator is adjusted so that the difference frequency is audible, that is, does not exceed about 10,000 cycles per second, the other three frequencies are so high that they are inaudible and the signals are then reproduced in the form of short or long audible notes, comprising the dots and dashes of the code.

But it is also possible to change the amplitude, frequency, or phase of a continuously transmitted carrier for the transmission of intelligence. This process is termed *modulation.* Amplitude modulation, where the carrier amplitude is varied in accordance with the amplitude and frequency variations of speech and

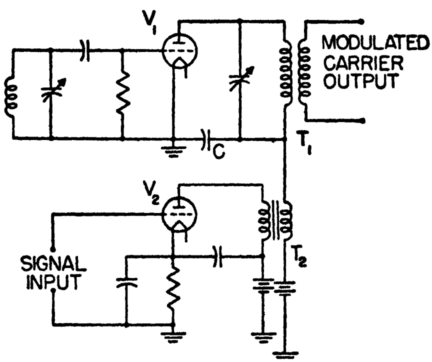


FIG. 3–24. Simplified circuit of an amplitude-modulated oscillator.

music, is commonly used in radiobroadcasting. A simple circuit, which shows how amplitude modulation may be accomplished in the anode circuit of an oscillator, is given in Fig. 3–24. Tube V_1 is the high-frequency oscillator, or it may be an amplifier tube whose grid is excited by an oscillator. A coupling transformer T_2, in the anode circuit of the modulator tube V_2, applies the signal voltage to the anode circuit of V_1, and the modulated carrier appears in the secondary winding of transformer T_1. The capacitor C provides a return circuit for the high-frequency component of the oscillator anode current.

In amplitude modulation the tuned-in signals are amplified, mixed with a voltage from a local oscillator for added selectivity, again amplified, then demodulated to remove the carrier—a process known as detection—and finally the remaining voice and music frequencies, in the form of an audio signal, are further

amplified and reproduced. The ordinary radiobroadcast receiver that accomplishes these functions is known as a superheterodyne receiver; it was developed by E. H. Armstrong in 1919. However, lightning and man-made electrical disturbances also consist of high-frequency oscillations that vary in amplitude and are

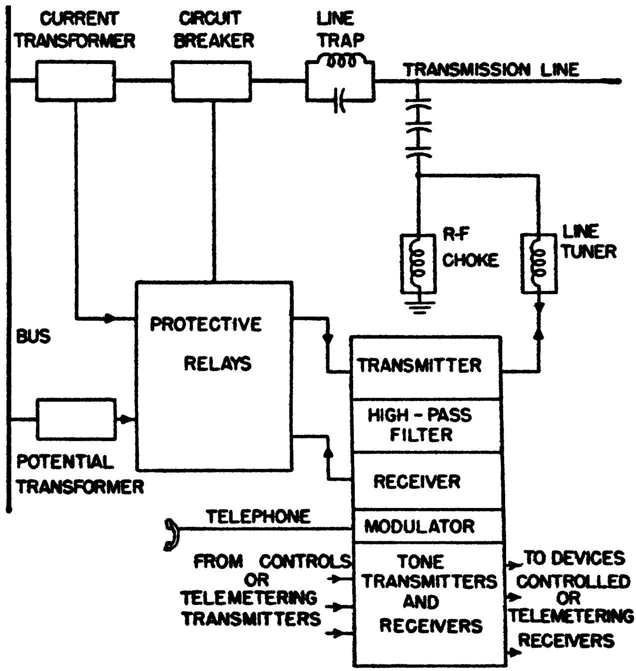


FIG. 3-25. Block-type functional diagram of a carrier-current system.

received with the carrier. This led to the development of frequency modulation, wherein a carrier maintains a constant amplitude but varies in frequency in accordance with the amplitude and frequency of the signal; it results in improved signal-to-noise reception.

A radiated carrier may be used as a measuring means. For instance, devices responsive to temperature, barometric pressure, or humidity are mounted in a meteorological balloon and their changes modify the amplitude or frequency of an audio-frequency oscillator, the output of which modulates a high-frequency oscillator. The signal is radiated, and after reception and demodulation the audio signal is measured or recorded.

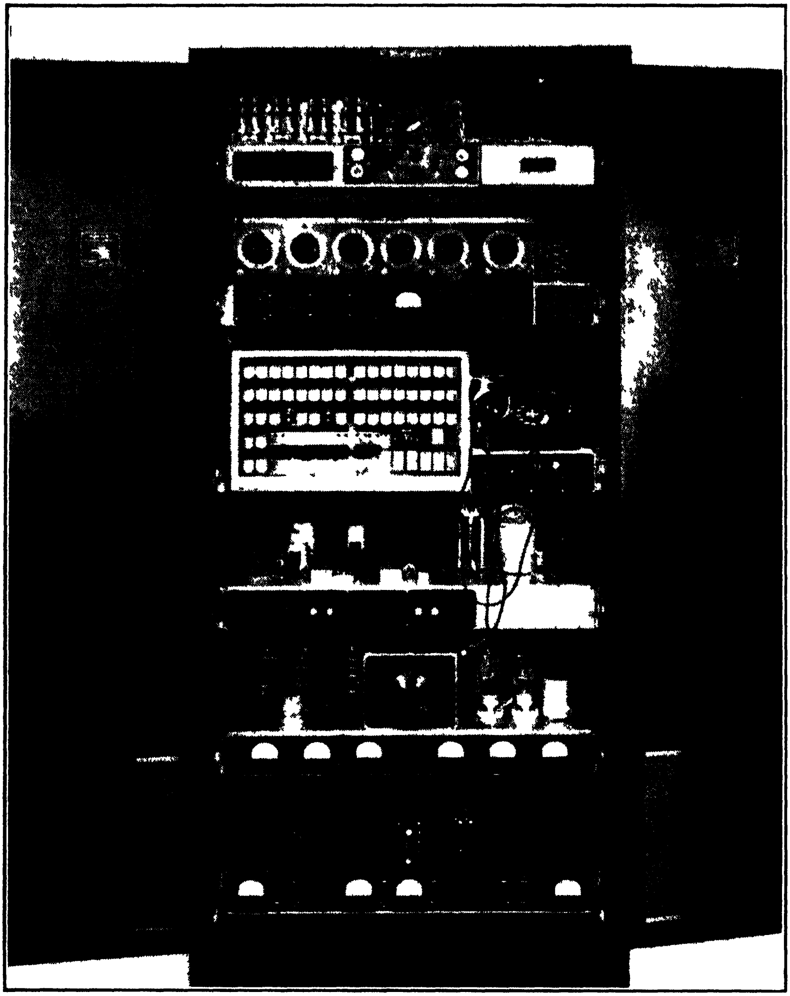


FIG. 3-26. Carrier-current equipment for telephony, control, and metering over a high-tension transmission line. *Courtesy Westinghouse Electric Corporation.*

Low-frequency carrier currents do not radiate well but confine nearly all their energy to conductors; such carrier-current installations use frequencies in the range from 50 to 150 kilocycles per second. In carrier-current telephony, a large number of telephone conversations, any one of which uses speech modulating

frequencies of 5 kilocycles or less, are carried simultaneously over a pair of conductors or a coaxial cable with the aid of as many different noninterfering carrier frequencies as there are conversations. Any particular channel is responsive only to a narrow frequency range, that is, to a particular carrier frequency, because of filters in the receiving equipment; therefore, not only does such a system lend itself to multichannel communication, control, and metering operations over a pair of conductors but the same conductors are actually used to supply commercial power. A simplified block-type diagram of a carrier-current system adaptable to a number of functions is shown in Fig. 3–25, and an illustration of the equipment is given in Fig. 3–26.

The high-frequency carrier is connected to the high-voltage transmission line through coupling capacitors that pass practically no current at the power frequency. These capacitors and the line traps or resonant circuits, which are tuned to offer a high impedance to carrier currents and which confine the carrier to a specific section of the power line, are shown in Fig. 3–27. Audio-frequency tones are provided for the remote control of standard equipment, for example to start or stop motors and generators, to switch capacitors, or to perform any other of a group of operations, and, if channels are required for telemetering kilowatts, voltage, phase angle, reactive power, hot-spot temperature, or transformer tap-changer positions, these, too, can be provided. As many as ten of these functions can be performed by utilizing only one carrier. If a maximum of only four tone channels is needed, they may be spaced in the frequency-modulating band below 500 cycles and filters may then be installed which will still permit acceptable speech transmission by using the voice frequencies in the remainder of the audio-frequency range above 500 cycles. A voice or code signal is used as a calling means. Carrier current on long power lines, and on pilot wires on short lines, offers a practical means of using a single relay with an electronic control unit for quickly and efficiently detecting and clearing all types of phase and ground faults. In a given case a carrier voltage signal of 100 volts, which is equivalent for that line to an input of 20 watts, is attenuated or reduced to 10 volts in traversing 200 miles; the received signal is still 100 times the average noise level of the line.

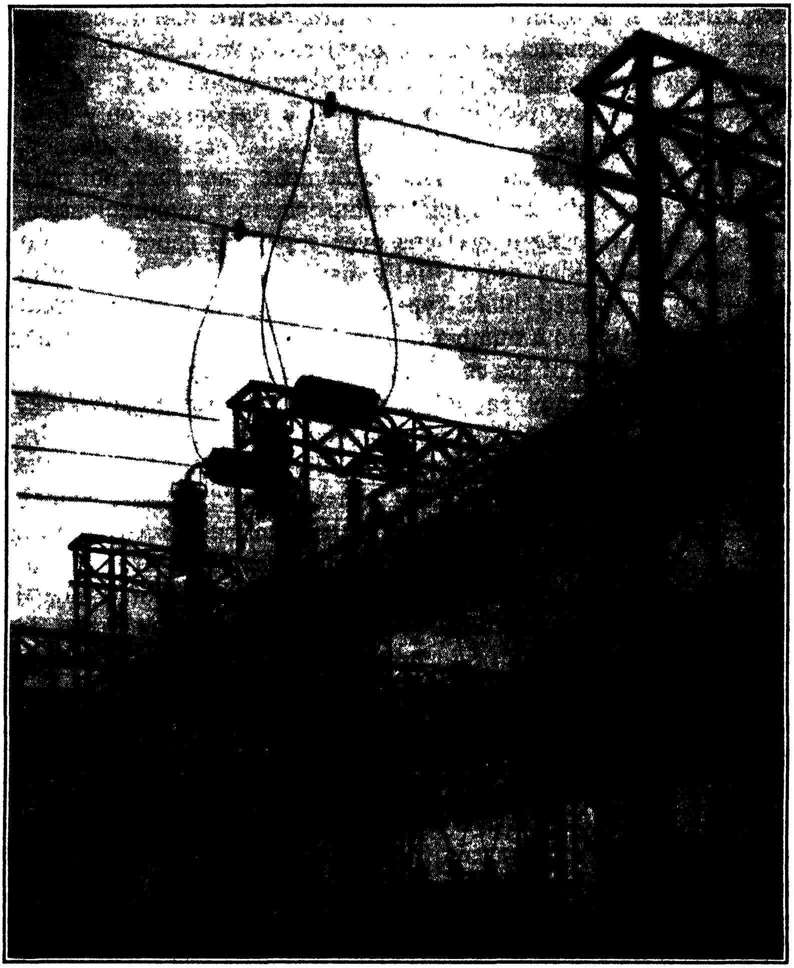


FIG. 3-27. Coupling capacitors and line traps used with carrier system on high-tension lines. *Courtesy Westinghouse Electric Corporation.*

3-10. Special-duty Oscillators

When an oscillator is used for broadcasting, in carrier-current work, in precision measurements, or where the frequency must remain precise and constant over a long period of time, the circuit is modified to prevent frequency drift. Quartz crystals have a piezoelectric property, that is, a wafer or plate of the material when subjected to mechanical stress will produce a voltage

between the opposite faces of the plate. Conversely, a voltage applied across the faces produces mechanical deformation of the plate or crystal. An alternating mechanical stress produces an alternating voltage, and an alternating voltage applied to the crystal produces mechanical vibrations. It is possible to produce crystals of various characteristics and temperature coefficients

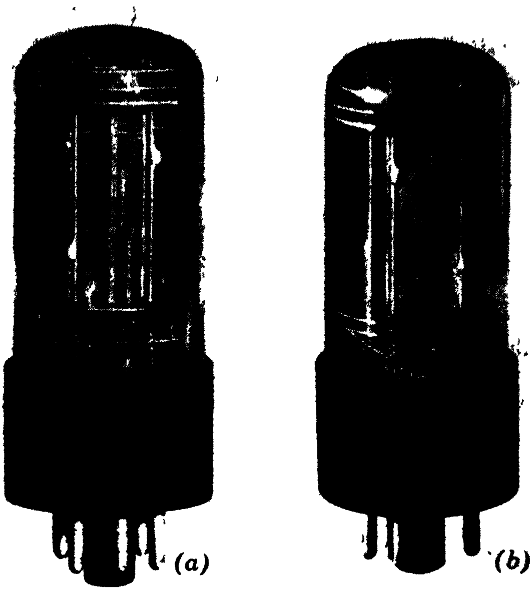


FIG. 3–28. Two views of a duplex quartz crystal typical of the type used in carrier telephone systems. *Courtesy Bell Telephone Laboratories, Inc.*

by cutting the plates at certain angles from the original quartz crystal. By making a specific cut through a definite angle of one of the crystal axes, a zero-temperature-coefficient crystal is produced. Figure 3–28 shows two views of a duplex crystal having a relatively low periodicity and designed for operation in telephone carrier systems.

A *crystal-controlled oscillator* coupled to an amplifier is shown in Fig. 3–29 and operates in the following manner. Whenever there is a variation in the anode current, the anode voltage changes, a voltage surge passes through the grid-anode interelectrode capacitance to the crystal surfaces, and the crystal is

deformed. At the conclusion of the surge, the restoration of the crystal to its original shape develops a voltage across its faces which is transmitted through the crystal holder to the grid and amplified by the tube. A portion of the output in the anode circuit is again fed back, and sustained electrical oscillations result. The grid has a voltage impressed on it at a frequency corresponding to the natural frequency of the crystal which functions analogously to a resonant circuit, the energy being stored alternately in mechanical and electrical form. The natural frequency of the crystal depends on the thickness of the wafer;

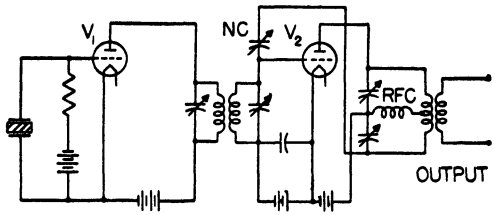


FIG. 3–29. Circuit of a crystal-controlled oscillator coupled to an amplifier.

high frequencies result from the use of thin crystals. Crystal-controlled oscillators will easily maintain an accuracy of 0.002 per cent.

Reversed feedback or *degeneration* is obtained by applying an opposition voltage along with the signal voltage to the grid of a triode. The tuned-grid tuned-anode amplifier, shown in Fig. 3–29, is inherently an oscillator and obviously would fail to function as an amplifier if the tube were permitted to oscillate. Since anode-to-grid coupling is achieved by impressing a voltage across the grid-anode capacitance, the coupling can be neutralized by impressing an equal and opposite voltage across that capacitance. Many neutralizing circuits have been devised, but the one shown in the figure is typical. The primary winding of the output transformer in the amplifier anode circuit is tapped, and voltage is supplied to the anode through a high-frequency choke *RFC* connected to the tap. The lower terminal of the winding has a voltage polarity 180° displaced from the top terminal; that is, one end of the winding is positive when the other is negative, and so the lower terminal is connected to the grid through a neutralizing capacitor *NC*. With a suitable winding on the transformer and proper adjustment of *NC*, the resultant

feedback voltage at the grid is zero and oscillation is prevented.

The *multivibrator* is a pulse generator used in measurements and as a foundation unit in radar and navigation equipment. It consists of two tubes connected in a circuit similar to a two-stage resistance-capacitance-coupled amplifier, but with the output of one stage coupled to the input of the other as shown in Fig. 3-30. Each tube conducts alternately; one tube conducts while the other is inoperative. The pulsing frequency is determined by the rate of discharge of the coupling capacitors, and no tuned circuits are used.

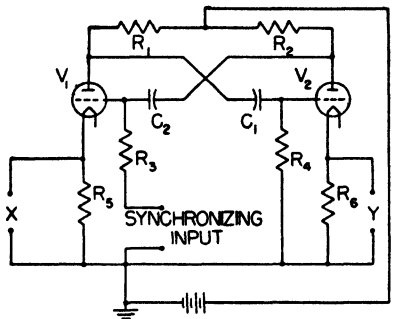


Fig. 3-30. Circuit of a multivibrator.

An uncontrolled multivibrator has a connector placed across the input terminals and operates as follows: During the interval when tube V_1 conducts and tube V_2 does not conduct, capacitor C_2 is charged from the power supply through R_2, V_1, and R_5. Also, the previously charged capacitor C_1 discharges slowly through V_1, R_5, and R_4, and the ensuing voltage drop across R_4 maintains the grid of V_2 at a sufficiently low negative potential to prevent the flow of anode current through V_2. When the grid voltage on tube V_2 becomes less than the cutoff value, V_2 starts to conduct, the voltage drop across R_2 increases, and the anode voltage of tube V_2 decreases. Since the charge on capacitor C_2 cannot change instantaneously, the lower anode voltage across tube V_2 impresses a negative voltage on the grid of tube V_1 that reduces the anode current through that tube. The decreased anode current through V_1, in turn, produces a decrease in voltage drop across R_1 and an increase in the anode voltage of tube V_1. As the anode voltage of V_1 rises, the grid voltage of tube V_2 also becomes more positive and the anode current through V_2 increases. The action is cumulative and the current through tube V_2 increases almost instantaneously to its maximum value, and simultaneously the current through V_1 decreases to zero.

During the succeeding interval capacitor C_1 charges by grid

conduction through R_1, V_2, and R_6, and capacitor C_2 discharges slowly through the anode circuit of V_2, R_6, and R_3. When the grid voltage on tube V_1 becomes less negative than the cutoff voltage, anode current begins to flow through that tube and the decreasing anode voltage of tube V_1 initiates the decrease of current through tube V_2. As before, the action is cumulative and the anode current through tube V_1 rises quickly to its maximum value while the anode current through tube V_2 drops to zero. This completes one cycle of operations.

The output voltage may be taken across either load resistor, R_1 or R_2, and is symmetrical in waveform if the capacitors and the grid resistors of both tubes have correspondingly similar values. The waveform approaches a square or rectangular form. If a suitable high-frequency voltage is connected to the input terminals, the output consists of a submultiple of the input frequency, and the circuit may, therefore, be used as a *frequency divider*. This control is brought about by the trigger action of the superimposed high-frequency voltage on the normally varying grid voltage of tube V_1. By adjusting the magnitude of the input voltage, a multivibrator can be made to synchronize or lock-in easily at any submultiple frequency up to about $\frac{1}{10}$ of the synchronizing or control frequency.

As the anode current of either V_1 or V_2 alternately reaches saturation to be followed an instant later by reduction to cutoff, the voltage drops across the cathode resistors R_5 and R_6 also vary in conformity with that change. These changing cathode biases may be used to operate alternately two amplifier tubes by simply inserting either voltage, as shown at X and Y, in the respective amplifier cathode circuits without using separate cathode biasing resistors in those tubes. Such a circuit becomes a simple *electronic switch* that permits alternate, periodic operation of one amplifier circuit while the other remains inoperative. Switching is accomplished at the multivibrator frequency, and this, in turn, may be accurately controlled by the frequency of the synchronizing input voltage.

3-11. Timing Circuit Fundamentals

Practically all electronic timers are based on the fact that the voltage across a capacitor, either during charge from a constant voltage supply or during discharge through a resistor, is a func-

tion of time. The charging current depends on the momentary voltage across the capacitor, and this, in turn, on the charge; the current is large when the voltage is zero and becomes less as the voltage across the capacitor rises. The voltage V_c across a charging capacitor was given in Sec. 1–12 as

$$V_c = E_B(1 - \epsilon^{-t/RC}), \qquad (1\text{–}11)$$

where E_B is the supply voltage, ϵ is the Napierian base, t is the elapsed time in seconds after the circuit is closed, R is the series resistance in ohms, and C is the capacitance in farads. During the discharge of a capacitor, the voltage V_d across it is given by the expression

$$V_d = E_B\epsilon^{-t/RC}, \qquad (3\text{–}15)$$

where t is the elapsed time in seconds after the circuit is opened.

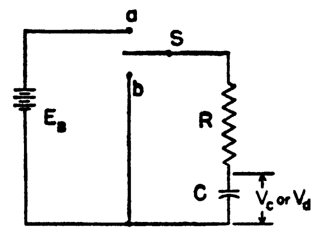


FIG. 3–31. Simple circuit for capacitor charge and discharge.

A circuit used to determine the charge and discharge characteristics of a capacitor is shown in Fig. 3–31. When the switch S is thrown to position a, the capacitor C is charged through resistor R; if the switch is then placed in position b, the capacitor discharges through the resistor. The

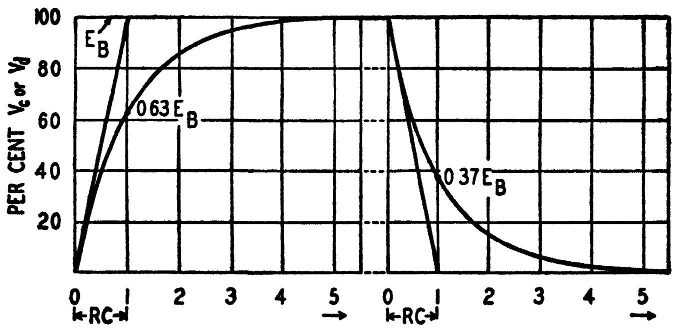


FIG. 3–32. Typical charge and discharge characteristics of a capacitor.

voltage V_c or V_d across the capacitor during charge or discharge may be recorded on an oscillograph. Typical curves for both charge and discharge are given in Fig. 3–32.

If $t = RC$ in Eq. 1–11, the exponent becomes equal to -1 and then $V_c = E_B - 0.37E_B = 0.63E_B$. The product RC is known as the *time constant* of the circuit; it is the time in seconds required to charge the capacitor to 63 per cent or to discharge it to 37 per cent of the supply voltage.

The slope of the charging curve at any instant is the first derivative of Eq. 1–11, or

$$\frac{dV_c}{dt} = -\frac{E_B\epsilon^{-t/RC}}{RC} = -\frac{E_B - V_c}{RC}. \tag{3–16}$$

At time $t = 0$, the slope is $-E_B/RC$. The ratio of the slope of the curve at any time t to that at time $t = 0$ is $\epsilon^{-t/RC}$ or $(E_B - V_c)/E_B$. Consequently, when the capacitor is charged through a resistor, the relationship between voltage and time is exponential. The approximation to linearity of the charging curve shown previously in Fig. 1–24 can now be evaluated. If the striking voltage V_c of the gaseous tube is 100 volts and the supply voltage has a value of 400 volts, then $(E_B - V_c)/E_B$, or the ratio of the two slopes, is 0.75. The departure from linearity is, therefore, 25 per cent. But if the charging current is regulated so that the voltage V_c is made to rise at a constant rate of E_B volts per RC seconds, that is, with the slope equal to the value it has at $t = 0$, then the capacitor will be fully charged in RC seconds. This condition is met by making the charging current constant.

When high-precision timers are designed, the choice of the capacitor is quite important because all capacitors permit a small leakage current to flow through the dielectric. This current is equivalent to one that would flow through a high resistance in shunt with the capacitance. We may assume that the switch S in Fig. 3–31 is located at an intermediate position between a and b after the capacitor has been charged. The discharge equation, Eq. 3–15, can be applied in this case by considering the resistance R to be negligible and replaced by the leakage resistance r. Differentiating the equation with respect to time, we obtain

$$\frac{dV_d}{dt} = -\frac{E_B\epsilon^{-t/rC}}{rC} = -\frac{V_d}{rC}, \tag{3–17}$$

or

$$-\frac{dV_d}{V_d} = \frac{dt}{rC}. \tag{3–18}$$

Applying incremental values ΔV_d and Δt in Eq. 3–18, the approximate percentage change for a 2-microfarad paper-dielectric capacitor, having a leakage resistance of 30 megohms and operating over a time interval of 6 seconds, is $\frac{6}{(30 \times 10^6)(2 \times 10^{-6})}$, or 10 per cent, which is an appreciable error. Special high-grade ceramic, mica, and pyranol-filled capacitors with low dielectric losses and leakage are used in precision timers to insure uniform time intervals.

The similarity between capacitive and inductive circuit behavior may be seen from the current rise and decay equations which are derived when an inductor in series with a resistor is connected to, and later disconnected from, a constant voltage source. The instantaneous current i_r in amperes during current rise is given by the equation

$$i_r = I_m(1 - \epsilon^{-Rt/L}), \tag{3–19}$$

and the instantaneous current i_d in amperes during the time the current decreases is

$$i_d = I_m\epsilon^{-Rt/L}, \tag{3–20}$$

where I_m is the maximum current in amperes, ϵ is the Napierian base, R is the resistance in ohms, L is the inductance in henries, and t is the time in seconds from the instant the circuit is either closed or opened, depending on the case in question.

The time constant, that is, the time required for the current through the inductor to rise to 67 per cent in the one case or to fall to 37 per cent of the maximum in the other, is L/R seconds. Capacitors are preferred to inductors in timer circuits because of their smaller size and greater ease of adjustment.

3–12. Electronic Timers

A simple, compact, and sturdy electronic timer is illustrated in Fig. 3–33, and the circuit is shown in Fig. 3–34. This timer operates the relay contacts a definite time interval after the switch is closed.

While the switch S is in the open position, the capacitor C_1 is charged by grid rectification because the grid is positive with respect to the cathode during every other alternation. The charge, although dissipated slowly through R_4, is maintained at

a value dependent on the setting of the potentiometer R_1. Timing begins when the switch is closed. The cathode is connected to the line and C_1 continues to discharge through R_4 until the grid

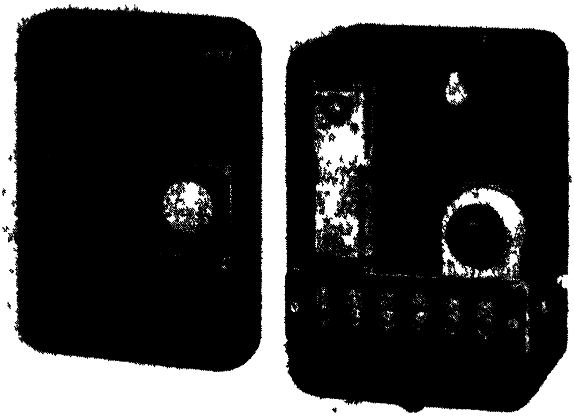


FIG. 3-33. Vacuum-tube time-delay relay. *Courtesy General Electric Company.*

voltage reaches a point where sufficient anode current passes through the tube to operate the relay. Anode current flows only when the anode is positive with respect to the cathode, but during

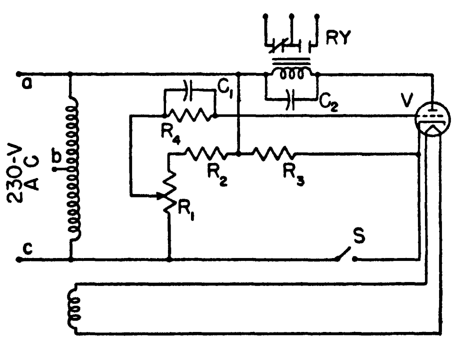


FIG. 3-34. Circuit of time-delay relay.

those alternations a portion of the line voltage, determined by the voltage drop across the lower portion of R_1, is also impressed on the grid through resistor R_4. Therefore, the position of

the slider arm determines the original charge on C_1 as well as the value to which the capacitor must discharge before conduction occurs. The relay operates a single-pole double-throw switch. A capacitor C_2 is connected in parallel with the relay to prevent armature chatter. The timer will reset in a fractional part of a second for another complete interval if the switch is opened before the timing is completed. Timing relays of this type are made in various time ranges from a minimum of about 0.045 second to a maximum of 2 minutes, depending on the setting of the potentiometer R_1 and the values of the capacitor C_1 and resistor R_4; each timer has a range adjustment of 20 to 1.

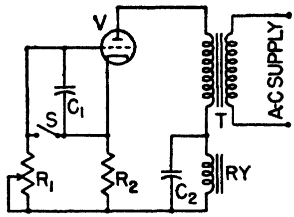


FIG. 3–35. Circuit of a timer which operates on a momentary closure of the switch.

The timer circuit shown in Fig. 3–35 causes the relay to operate at a given time interval after the switch S is momentarily closed and released. In the original open-switch position, the capacitor C_1 is charged through the adjustable resistor R_1, and the grid potential reaches a sufficiently negative value to reduce the anode current to prevent relay operation. When the switch is momentarily closed to discharge the capacitor, the grid is placed at cathode potential and the relay operates and remains in the operative position while the capacitor C_1 again charges through resistor R_1. At a given negative grid potential, corresponding to a certain capacitor charge, the anode current is reduced to a value that causes the relay to return to normal. The capacitor C_2 is used, as in the previous circuit, to prevent relay-armature chatter.

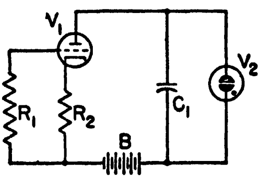


FIG. 3–36. Circuit of a triode used as constant current device.

The simple relaxation oscillator generates a periodic voltage that deviates from linearity as was shown in the preceding section. In order to obtain a linear relationship of voltage with respect to time, it is necessary to charge the capacitor with a constant current. The vacuum triode may be connected as shown in Fig. 3–36 to achieve this result. No conventional anode load resistor is used in the circuit; the cathode resistor R_2, since it is

in the anode circuit, may be considered as the load. Its value ranges up to several hundred thousand ohms. A circuit of this type is known as a *cathode follower* and is a current feedback amplifier, the instantaneous grid potential being proportional to the anode current. With the capacitor C_1 discharged, the momentary anode current charging the capacitor has a tendency to be large. Such a current, however, also tends to set up a large cathode bias across R_2 which, being impressed on the grid through the resistor R_1, promptly tends to reduce that current. The net effect is to hold the anode current constant during the time the capacitor charges. When the critical firing voltage of the gaseous-discharge tube V_2 is attained, the capacitor discharges and the cycle repeats. With a triode, such as the 6F5, which

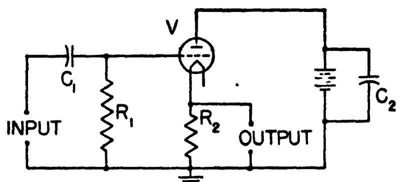


FIG. 3–37. Circuit of a cathode follower used as a degenerative amplifier.

has a high amplification factor, a practically linear relationship of capacitor voltage versus charging time is obtained.

A cathode follower circuit may also be used as a degenerative amplifier, Fig. 3–37. The capacitor C_1 and the resistor R_1 are the conventional input components. It should be noted that the cathode resistor R_2 is not bypassed by a capacitor. A positive voltage increase on the grid causes an increase in anode current which makes the cathode connection of R_2 more positive with respect to the ground. When the grid is made negative, the cathode becomes less positive; consequently, the output voltage follows the input voltage; this explains the derivation of the name of the circuit. The voltage variation across the load resistor in a conventional amplifier is displaced 180° from the input voltage, but in the cathode follower circuit the input and output voltages have the same phase relationship. The circuit may also be used to couple a high-impedance circuit, operating into the high-impedance grid circuit of a triode, to a low-im-

pedance output circuit connected across a low-valued cathode resistor. But whatever the value of the cathode resistor, the amplification of the circuit is always less than unity.

Problems

1. Plot the relation between percentage of amplification and load resistance in terms of tube resistance as given in Eq. 3–10. Use percentage of e_p/e_g as ordinates.

2. What is the percentage of amplification in a voltage amplifier when the load resistance is made equal to the tube resistance?

3. Prove that the power output of a vacuum triode is

$$P = \frac{(e_{b\,\max} - e_{b\,\min})\,(i_{b\,\max} - i_{b\,\min})}{8},$$

where the max subscripts denote the sum, and the min subscripts the difference, of the direct and the peak alternating voltages and currents.

4. From the description of operation and on the basis of the circuit diagrams, Figs. 3–15 and 3–16, plot approximate characteristic curves of amplifiers which are (*a*) resistance-capacitance coupled, (*b*) impedance coupled, (*c*) transformer coupled, (*d*) direct coupled.

5. Trace the following circuits of the direct-coupled amplifier shown in Fig. 3–16(*b*): (1) grid circuit of V_1, (2) anode circuit of V_1, (3) grid circuit of V_2, and (4) anode circuit of V_2.

6. In the oscillator relay circuit of Fig. 3–22, an increase in the line voltage produces an increase in the anode current of the oscillator tube V_1. Does this cause the relay to operate? Determine whether the bias on the amplifier tube V_2 increases or decreases when the line voltage increases.

7. In determining the suitability of a level-sensing device similar to the one described in the last portion of Sec. 3–8, ascertain from reference works the value of the dielectric constants of (*a*) olive oil, (*b*) phenol, (*c*) ethyl alcohol, (*d*) glycerin, (*e*) gasoline of two different octane ratings.

8. Draw a functional block diagram of a superheterodyne radiobroadcast receiver. In which block or blocks must the receiver be tuned to receive various broadcast frequencies?

9. It is desired to operate the time-delay relay shown in the circuit diagram Fig. 3–34 on 115 volts alternating current. To which of the two connections, *a–b* or *b–c*, should the line be connected? Does the change in connection from 230 to 115 volts affect the time interval of the relay for a given knob setting? Why?

10. In an electronic timer of the type shown in Fig. 3–34, the timing interval depends on the time constant R_4C_1. In a specific instance, the relay operates when the voltage on the capacitor has decreased to 40 per cent of the original value. Capacitor C_1 has a value of 2 microfarads and resistor R_4 has a value of 1 megohm. What is the time interval between switch closure and relay operation?

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4

Multigrid and Special Vacuum Tubes

Previous reference has been made to duplex tubes, such as the duodiode which serves as a full wave rectifier, and the twin triode used in amplifier circuits. The duodiode-triode and other multiplex tubes in a common envelope are available for application where space is at a premium or where cathode-heater power needs to be conserved. There are other tubes, however, that incorporate electrodes additional to the ones normally used in the triode, usually in the form of additional grids. Special vacuum tubes have also been designed that contain control electrodes, or others that are arranged so that external magnetic control means cause the electrons to move as a beam; they play an important role in television, microscopy, and instrumentation.

4-1. Screen-grid Tube

One of the major limitations in the performance of the vacuum triode is caused by the grid-to-anode capacitance. Its effect is particularly harmful in a high-frequency amplifier and may even cause the tube to act as an oscillator; it limits the tube designer to low amplification factors. The problem finds a partial solution in the *screen-grid* tube, or tetrode, where a screening electrode is placed between the control grid and the anode. The screen consists of a simple wire grid, or, more usually, the anode is almost completely enclosed by a screen composed of an outer and an inner portion. Introduction of the screen grid reduces the grid-to-anode capacitance from 6 to 8 micromicrofarads to the negligible value of about 0.008 micromicrofarad or

less. Figure 4–1 illustrates the electrodes of a simple screen-grid tube.

As shown in the amplifier circuit, Fig. 4–2, the screen grid is connected to a fixed positive potential somewhat lower than the anode potential. A capacitor C_3, connected between the screen

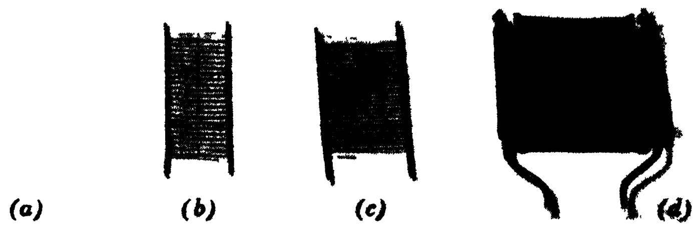


FIG. 4–1. The four electrodes of a screen-grid tube; (a) cathode; (b) control grid; (c) screen grid; (d) anode.

grid and the ground, places the grid at the cathode potential with regard to any alternating current in the anode circuit. Electrons, emitted by the cathode and passing the control grid, are accelerated uniformly toward the positively charged screen grid. Their velocity then carries them through the grid, and they strike the anode. This is an important point, for, in a triode, the

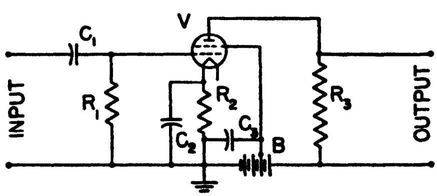


FIG. 4–2. Simple amplifier circuit using a screen-grid tube.

accelerating field is not constant since the anode voltage varies with the load, but in a tetrode the accelerating field remains constant because of the constant voltage on the screen grid.

Two anode-current anode-voltage characteristics of a typical screen-grid tube are given in Fig. 4–3. The data for these graphs were taken with the control-grid voltage and the screen-grid voltage held constant at the indicated values. We note that as the anode voltage is increased the anode current increases,

then decreases with a higher anode voltage, and subsequently increases again to a value that remains nearly constant. After the first current rise any increase in anode voltage causes the emitted electrons to acquire sufficient energy so that, when they strike or bombard the anode, other electrons are released or emitted by the anode. This process is termed *secondary emission.* It also occurs in the diode and triode, but, because the anode is

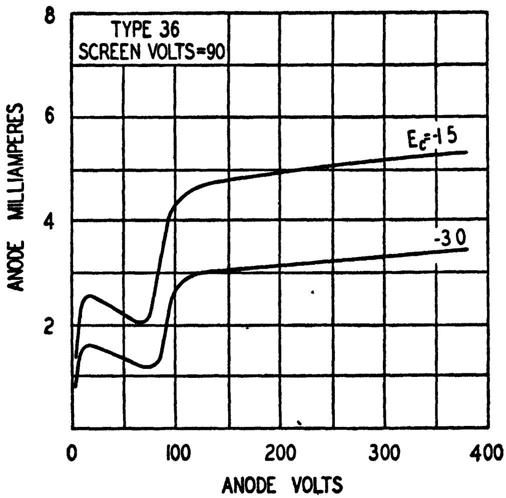


FIG. 4–3. Anode characteristics of a typical tetrode.

the only positive electrode in those tubes, the dislodged electrons return to that electrode. Throughout that portion of the characteristic in which the anode current decreases, the screen-grid potential is higher than the anode potential and many of the secondary electrons migrate toward the screen grid. At still higher anode potentials, the anode attracts more of the secondary electrons, with the result that the anode current increases to an almost constant value. The drooping portion of the characteristic is used in special oscillator circuits. Operation in that region is of interest because it represents a device with negative resistance; that is, an increase in anode voltage results in a decrease in anode current. Normally, however, a screen-grid tube is operated as an amplifier with anode voltages in the range between those slightly above the screen-grid voltage and the maximum anode voltage for which the tube was designed. In that range, the tube resistance is very high and practically

constant and, consequently, the tube requires a high-valued load resistor R_3 for maximum amplification.

4-2. The Suppressor-grid Tube

The irregularity in the initial portion of the characteristic of the screen-grid tube limits the permissible operating range of the anode voltage. This limitation is removed by introducing

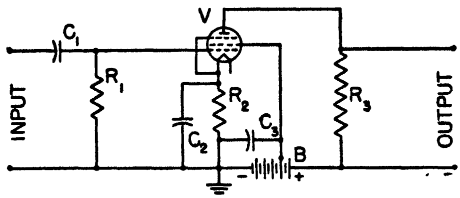


FIG. 4-4. Amplifier circuit using a suppressor-grid tube.

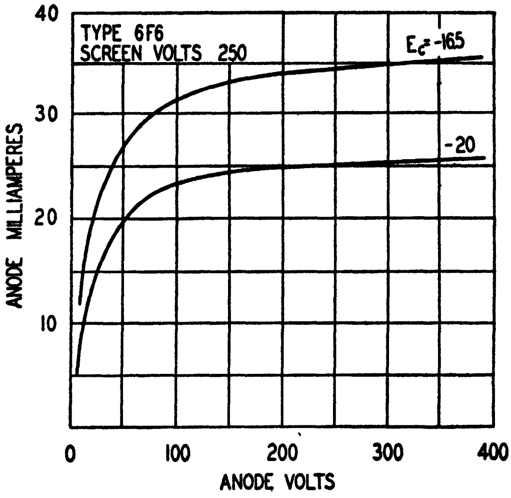


FIG. 4-5. Anode characteristics of a typical pentode.

an additional grid between the screen grid and the anode. This *suppressor grid*, which makes the tube a pentode, is connected to the cathode and therefore has a negative potential with respect to the anode. As a result of this the electrons that are produced by secondary emission encounter a field that attracts them towards the anode.

A simple pentode amplifying circuit is shown in Fig. 4-4, and a typical pentode I_B-E_B characteristic is given in Fig. 4-5. We

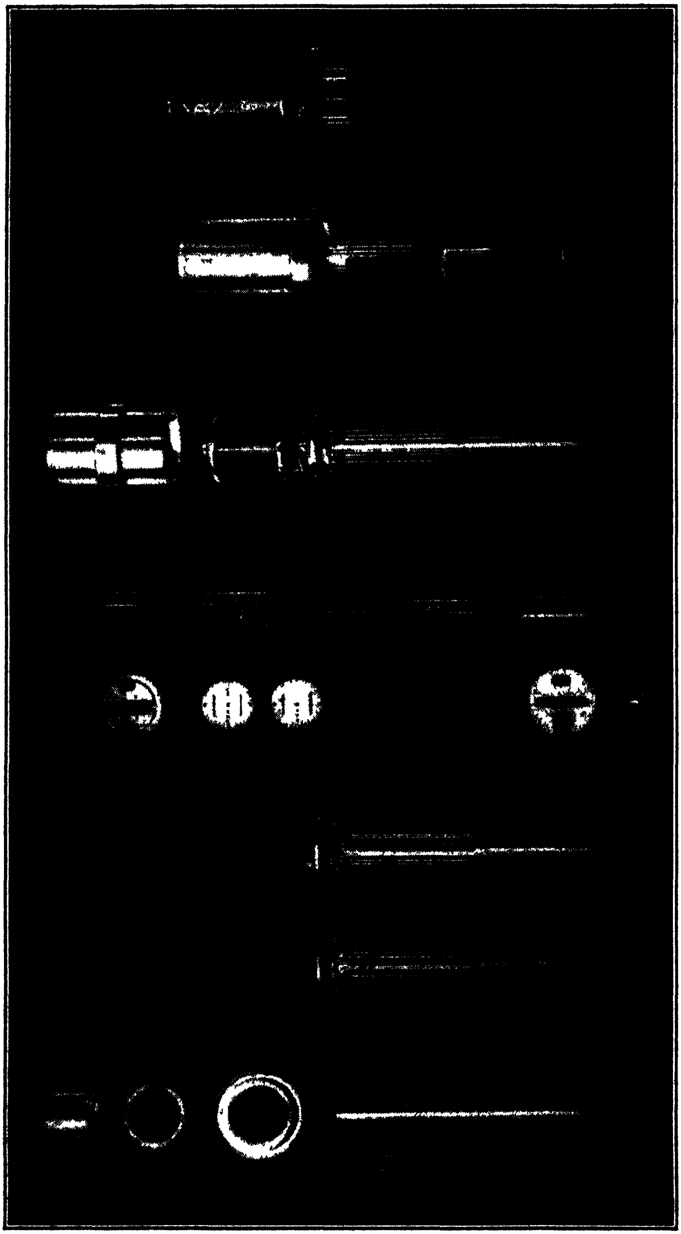


Fig. 4-6. Progressive steps in the assembly of a metal-type pentode. *Courtesy Radio Corporation of America.*

note that the anode voltage may be considerably lower than the screen-grid voltage without causing malperformance and that the permissible anode-voltage variation has been greatly extended. The practically constant and linear portion of the anode characteristic beyond the initial portion indicates not only constant tube resistance but also that the pentode is essentially a constant-current device; it is used in timing circuits where a uniform

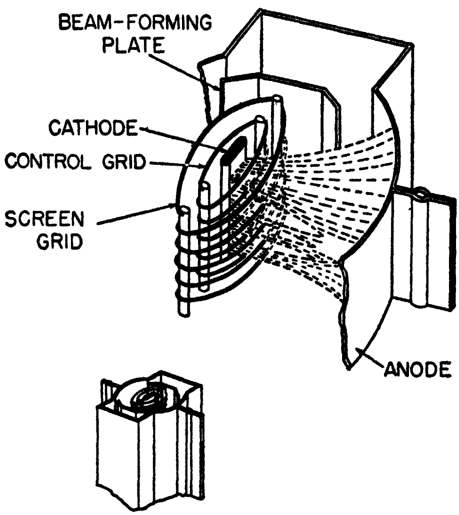


FIG. 4–7. Location of the electrodes within a beam power tube. *Courtesy Radio Corporation of America.*

charging rate is important. Because of their high amplification factors and freedom from causing circuit instability, millions of pentodes are used annually in radio and television receivers. Progressive stages in the assembly of a metal-type pentode are illustrated in Fig. 4–6. Such a tube is completely shielded. The same general design is also used in the construction of diodes, triodes, and other types of tubes.

Considerable distortion is introduced in the output of a pentode when it is operated at low anode voltages where the characteristic has a decided curvature. At these voltages, the suppressor grid deflects some of the electrons emitted by the cathode to the screen grid and destroys the desirable constant current versus anode voltage relationship. But a close approach to this ideal is achieved with the very sensitive, highly efficient *beam power*

tube. The tube, actually a tetrode as illustrated in the sketch of Fig. 4–7, is designed with the turns of wire of the screen grid in line with the turns of wire of the control grid. This keeps the screen-grid current to a minimum, and then, too, beam-forming side plates, which are connected electrically to the cathode, concentrate the electrons into sheets or beams. Electron density between the screen grid and the anode is very high because of this construction, and the electrons are slowed down or practically come to a stop between these electrodes. In other words, a virtual cathode is formed at that point from which the electrons move toward the anode. The electric field prevents any secondary electrons from reaching the screen grid, and the anode current remains essentially constant for all except extremely low anode voltages.

4–3. Magnetic Wire Recorder

A typical application of the pentode and the beam power tube is illustrated in the magnetic wire recorder shown in Fig. 4–8. Speech, music, and transient phenomena are translated into a correspondingly changing magnetic field which magnetizes a specially heat-treated steel wire, 0.004 inch in diameter, as it passes through a magnetizing head. The wire is unwound from one spool, magnetized, and rewound on another at the rate of 2½ feet per second; it is long enough to provide more than an hour's recording and can be increased easily to permit much longer recordings. The device differs from other tape or wire recorders in that the wire is magnetized longitudinally across a 0.002-inch airgap instead of transversely or perpendicularly and, also, by the fact that a 30-kilocycle alternating voltage is impressed on the magnetizing coil along with the signal during the recording. The superimposed high-frequency magnetic field tends to produce a linear relationship between the magnetizing force and the retentivity in the steel wire which would not otherwise exist. Consequently, high-fidelity recordings can be made on a relatively indestructible material; the wire retains its magnetization for a long time even though it is wound over other magnetized wire on the spool. The recording requires no subsequent processing and can be reproduced immediately after rewinding. Erasure is accomplished by subjecting the wire to a gradually decreasing magnetic field, similar to that used in

watch-spring demagnetization, just before the wire passes into the recording zone. When the switch is thrown from "record" to "listen," the same magnetizing head is used as a pickup device, but the high-frequency oscillator, not being required, is disconnected, and a loud-speaker, meter, or a visual indicator is connected in the output circuit.

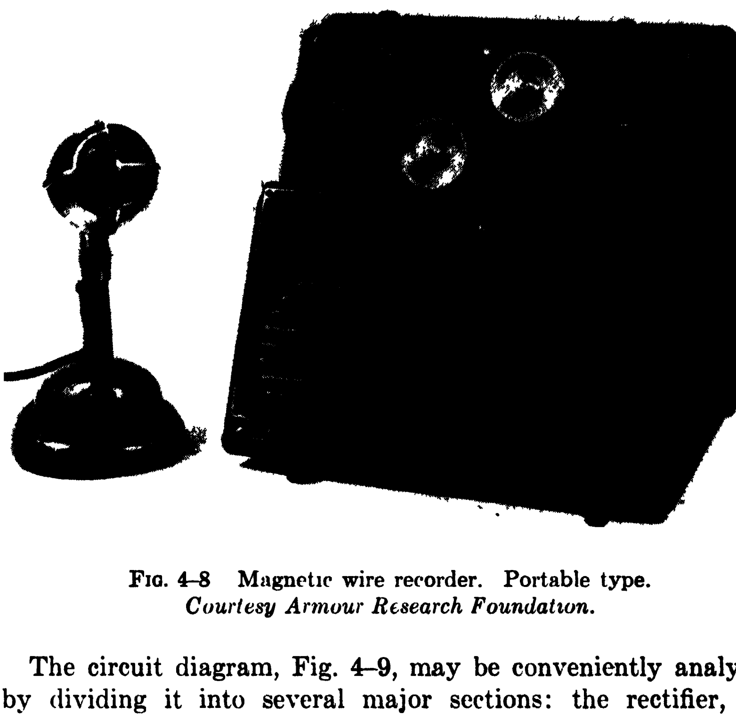


FIG. 4–8 Magnetic wire recorder. Portable type. *Courtesy Armour Research Foundation.*

The circuit diagram, Fig. 4–9, may be conveniently analyzed by dividing it into several major sections: the rectifier, the amplifier, the oscillator, the equalizing network, and the magnetizing head.

The rectifier tube V_1, connected as a conventional full-wave rectifier, supplies the various direct voltages. The circuit shows two pentodes V_2 and V_3 and a beam power tube V_4 in a three-stage resistance-capacitance-coupled amplifier. Tube V_3 has a variable grid resistor VC, which acts as a gain or volume control, connected across its input circuit. The beam power tube V_4 is arranged for a dual output; one exists through the output transformer to the loud-speaker or indicator when a section of the

multiple contact switch S, as shown in the circuit, is on the "listen" position. Also, the amplifier input is connected by means of another section of the switch to the recorder head. The second output path is through a coupling capacitor C_3, through the switch in the "record" position, through the equalizing network, and also through the lower oscillator coil and recorder coil to ground. For the latter path, the amplifier during

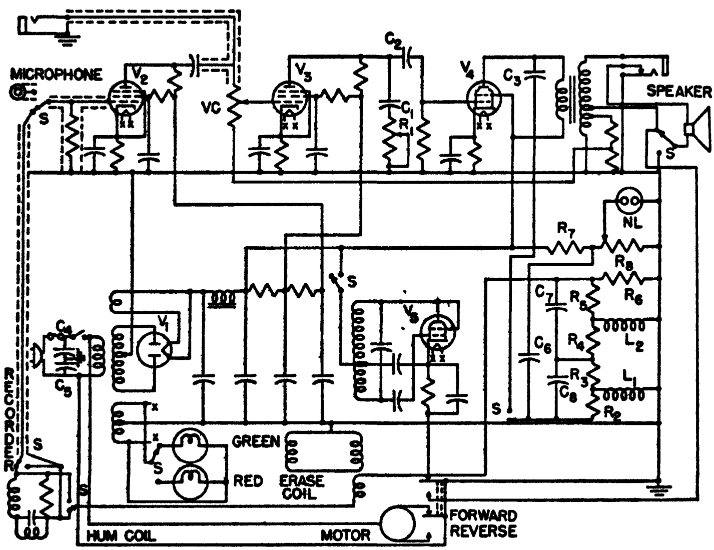


FIG. 4-9. Circuit of the magnetic wire recorder. Switch S is in the "Listen" position. *Courtesy Armour Research Foundation.*

recording is connected to a microphone or other suitable transducer. The equalizing network, consisting of C_7, C_8, R_2, R_3, R_4, R_5, R_6, L_1, and L_2, is used to obtain a rising voltage versus frequency output for a constant-amplitude voltage versus frequency input. The beam power tube V_5, with its screen grid connected to the anode, is used as the high-frequency oscillator.

A number of other circuit and mechanical refinements are incorporated in the device. The input circuits of the amplifier are shielded by encasing them in a grounded braid to avoid any unwanted or stray input signals. A hum-bucking coil, in series with the recorder, introduces an opposite phase voltage to neutralize any amplified residual alternating ripple voltage remaining in the d-c power supply. Two relays operate brakes

which stop the rotation of the spools whenever the wire stops. Transients are prevented from entering through the supply circuit by the two capacitors C_4 and C_5. The output signal voltage, together with a direct biasing voltage, is applied to a gain indicator lamp NL through R_7, R_8, and C_6; R_8 is adjusted so that the neon lamp just flashes when a recording is made at the proper output level. Red or green pilot lights indicate when the device is being used for either recording or reproducing, respectively.

4-4. Cathode-ray Tube

Many years ago it was discovered that when a high voltage is impressed on two electrodes of unequal size, one a point and the other a plate, in an evacuated tube the glass wall around the larger electrode fluoresces and the smaller electrode apparently emits rays that cast a shadow of the plate on the glass wall. Experiments disclosed that for some obscure reason the current passes through the tube more easily when the point is negatively charged, and from this the deduction was made that the fluorescence was due to rays emitted by the cathode. The name cathode ray persists, although it is now known that the action is due to electrons emitted by the cathode. The discovery led to the development of the *cathode-ray tube,* in which electrons are emitted from a cathode, accelerated to a high velocity, and tapered into a beam. The beam is focused to a point and causes fluorescence on a phosphor-coated screen located at one end of a bulb-shaped tube on its slightly curved inner surface. The beam is deflected easily and may be made to follow extremely rapid control-voltage variations; that is, the tube is a visual indicator of both steady and transient electric and magnetic phenomena. For purposes of analysis, we can consider the tube to be made up of three major components: the electron beam generator or electron gun, the fluorescent screen, and the control means that deflect the beam. These elements of the tube are shown in Fig. 4-10(*a*).

The electron gun contains an indirectly heated cathode with the emissive oxide coating applied to the cap end of the cylinder surrounding the heater; this construction produces electron emission in the desired direction. Intensity of the beam is regulated by the potential on an adjacent cylindrical, negatively

charged control grid. It is concentric with the cathode structure and has a small aperture through which the electrons pass. The emitted electrons are urged through the hole in the grid structure and focus just beyond the opening. The grid, therefore, is not only a control means but it also acts analogously to a double convex lens in optics, in that it concentrates the electrons into a

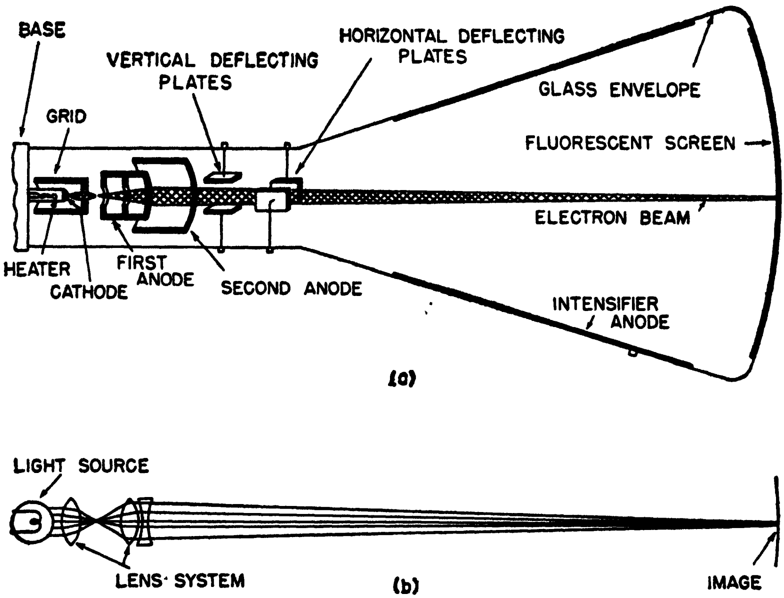


FIG. 4–10. (*a*) Sketch of the principal components of a cathode-ray tube; (*b*) components and their location in an analogous optical system.

narrow beam. See Fig. 4–10(*b*). The anode is also cylindrical and has an aperture as shown in the figure.

After the electron beam passes through the anode aperture, it again diverges and must be focused on the fluorescent screen by either a magnetic or an electric field. In the electromagnetic focusing system, a coil carrying a constant current surrounds the glass envelope just beyond the anode and produces the desired magnetic field. The interaction of this field, when properly adjusted, with the one surrounding the electron beam causes a deflection of the electrons so that they move in a path of a decreasing helical spiral and ultimately focus at a spot on the fluorescent screen. Structural simplicity, sharp spot definition,

and shorter tubes are achieved by means of this type of focusing, but it suffers from the disadvantage that the auxiliary circuits are more complex because of the power requirements of the coil. Electrostatic focusing is obtained by introducing a second, still more positively charged, accelerating anode which is so displaced with respect to the first anode that the electric field deflects the electrons so that they meet at a point on the screen. The optical analogy would be the introduction of an additional double convex lens followed by a double concave lens.

The voltage on the first anode is adjustable, and when changed, the field, and therefore the focus, of the equivalent electron lens is changed. Because of this, the first anode is often termed the focusing anode. In some early designs the first anode with its pinhole opening was divorced from the focusing anode; in the illustrated example they are combined in one unit.

Some of the energy resident in the electron beam is converted into light at the point where it strikes the fluorescent screen. Willemite, which glows with a green light, is commonly used in measuring devices; compounds of zinc sulphide, which produce nearly white light, are used in television tubes; and special phosphors, which produce blue light, are used for tubes where the trace is to be photographed. All phosphors have some persistence, depending on the material and on the electron-beam energy. Persistence varies in different types of tubes, and the choice of tube depends on whether it is to be used for the observance of repeating or transient phenomena. Secondary emission also occurs at the point where the beam strikes the screen. A positively charged graphite coating, as indicated in the figure, carries away any secondary electrons and also acts as an additional accelerating anode for the beam after it leaves the second anode. Frequently, a metallic, positively charged circular electrode, termed an intensifier ring, is used in conjunction with the graphite coating to act as an additional beam-accelerating means to increase the brilliance of the spot.

Either a magnetic or an electric field or a combination can be used by the input signal to deflect the beam. The majority of cathode-ray tubes are made for electric control because practically no current is required to produce a deflection, the control circuits are more simple, and inductance problems of the deflection coil are eliminated. This type of control requires two pairs of

deflecting plates, as shown in Fig. 4–10(*a*). The first pair of plates are mounted so that an applied voltage causes the beam to be deflected in a vertical direction; they are termed the vertical deflecting plates. The second pair of plates, mounted at right angles to the first pair, achieve a similar result in a horizontal direction and are termed the horizontal deflecting plates.

Any electron in the beam as it passes between the plates at a constant velocity is attracted towards the positive plate and deflected to an amount depending on the time it is in the field; that is, the deflection depends on the magnitude of the potential on the plates and on the length of the plates. But since the plate size is fixed, the deflection varies only with the plate potential. The *deflection sensitivity* of an electrostatically controlled cathode-ray tube is expressed as the ratio of the displacement in millimeters of the spot on the screen per volt of the applied potential on the deflecting plates. By applying suitable values of potential of the proper polarity to each pair of deflecting plates, the spot may be made to fall on any point of the screen. More significantly, if the potentials on the deflecting plates change to a different value, the spot of light changes almost instantaneously to the new position on the screen. If the potential varies and is repetitive, the spot position varies in conformity and appears without flicker as a continuous line or stationary pattern if the variation occurs at least 16 times per second.

4–5. Cathode-ray Oscilloscope

The combination of a cathode-ray tube, power supply, horizontal amplifier, vertical amplifier, sweep circuit, and suitable switching means is known as a *cathode-ray oscilloscope* or a *cathode-ray oscillograph*. The tube and auxiliary equipment are mounted in a shielded metal cabinet so that only the screen is visible, as shown in Fig. 4–11. The controls are located on the front panel. The *Y* controls are used in the designation of the first or vertical deflecting system; the *X* controls are used for the horizontal deflecting system. In the particular instrument shown in the figure the panel is divided into four portions. The tube screen, in the top portion, is overlaid with a transparent ruled graduate on which quantitative readings may be made. The second portion controls the electron beam. The toggle switch at the right is the main switch; the one on the left is in

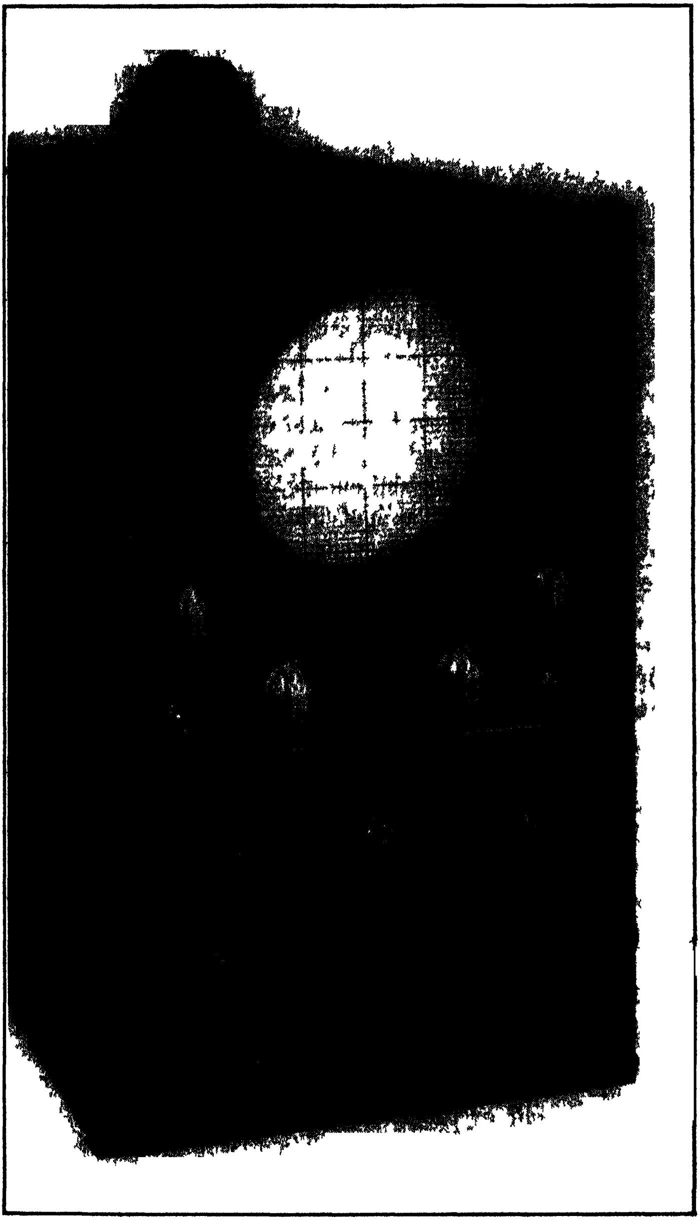


Fig. 4–11. Cathode-ray oscillograph *Courtesy Allen B Du Mont Laboratories, Inc.*

series with the cathode circuit of the cathode-ray tube and turns the beam on and off. The intensity control varies the grid bias by changing the value of the cathode resistor. Focus control is obtained by varying the voltage on the focusing anode with respect to that on the accelerating anode. Just above each toggle switch there is a control, connected to an adjustable slider on the cathode-bias resistor of either the vertical or horizontal amplifier; the output of each is connected to its respective deflecting plates. The initial position of the spot may be fixed at any location on the screen by the adjustment of these two controls; they vary the direct potentials of the plates with respect to the ground.

The time-base controls are mounted on the third portion of the panel. A relaxation oscillator that delivers a saw-tooth waveform voltage is located within the instrument, and, if desired, that voltage may be impressed on one pair of plates to produce a linear time variation of the spot while a varying and recurring voltage is impressed on the other pair of plates. The photographic reproduction, Fig. 4–12, shows an alternating signal voltage, impressed on the vertical deflecting plates, that causes the beam to move vertically in accordance with the magnitude and direction of the instantaneous alternating voltage while a relaxation oscillator voltage, which varies linearly in magnitude with respect to time and in synchronism with the signal frequency, is impressed on the horizontal deflecting plates and causes the beam to move periodically in a horizontal direction to the right. The resultant stationary trace of voltage has a sinusoidal waveform. Coarse frequency adjustment of the relaxation oscillator is made by varying the value of the capacitor; fine adjustment is obtained by altering the value of the resistor in series with the capacitor supply voltage. The figure shows one cycle on the screen for each sweep, but by suitable adjustment two or more complete cycles may be shown. If the sweep frequency is not precisely the same as that of the unknown voltage, the trace will not be stationary but will appear to move either to the right or the left, depending on whether the sweep frequency is too fast or too slow. The discharge of the capacitor through the gaseous tube takes place during a few microseconds; consequently, the fly-back time is very short and that trace is barely visible. A synchronizing-signal selector switch is lo-

cated to the left of the frequency controls. The switch arm, connected to the grid of the discharge tube, allows an external, the 60-cycle supply line, or an internal source voltage to be

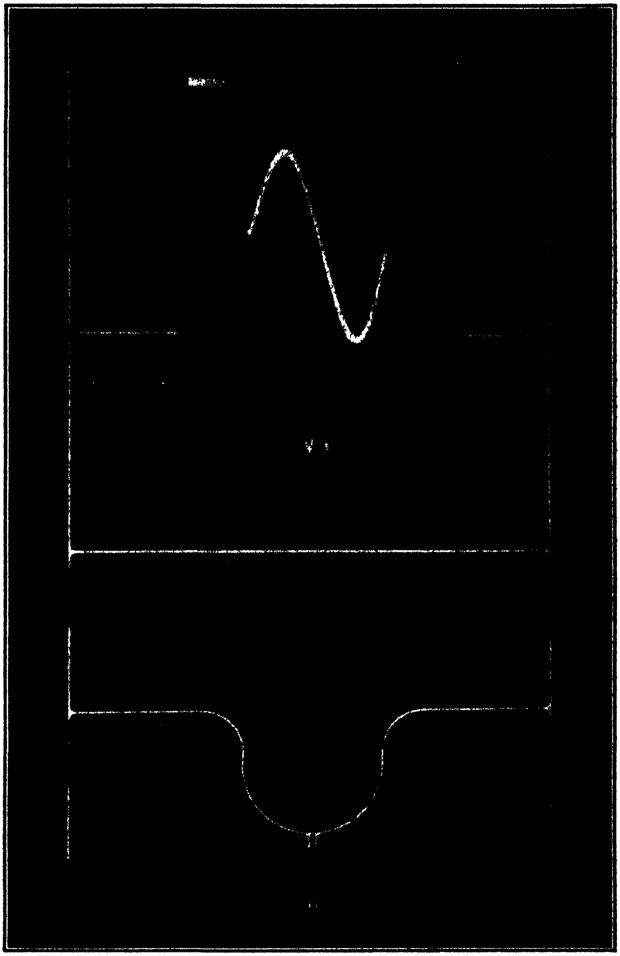


FIG. 4–12. Trace of an alternating voltage on the screen of an oscillograph. Lettering and graduations are made with phosphorescent material. *Courtesy Allen B. Du Mont Laboratories, Inc.*

selected as a trigger for the oscillator. The line-frequency position is used in the investigation of waveforms in devices that derive their power from the same source as the oscilloscope; the

trace shown on the screen was taken under this condition. Amplitude of the synchronizing-signal voltage is adjusted by the control on the right. Binding posts are provided to connect test and synchronizing-voltage leads.

The pilot light, signal input binding posts, gain control switch, and gain controls for the amplifiers, which supply the vertical and horizontal deflecting plates, are located on the lowest portion of

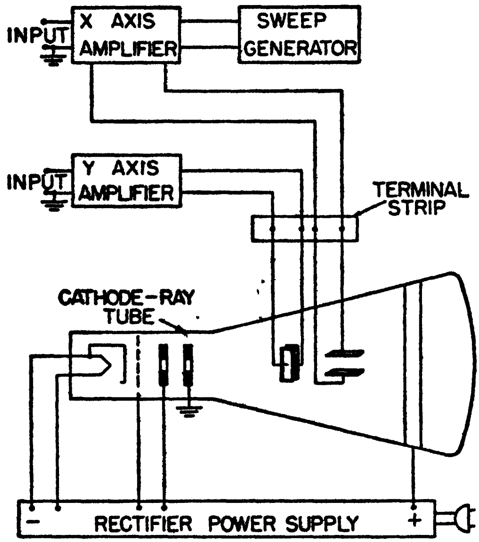


FIG. 4–13. Simplified diagram of a cathode-ray oscilloscope.

the panel. A gain control switch connects a resistor across the input circuit of the vertical deflection amplifier and is used to discriminate between large and small input voltages. The gain controls consist of variable potentiometers connected across the input stages of the vertical and horizontal deflection amplifiers.

A simplified block-type diagram of the oscilloscope is shown in Fig. 4–13. Heater and direct voltages, including those for the amplifiers and the sweep generator, are supplied by the power-supply unit. The accelerating anode is placed at ground potential in order to keep low potentials on the beam-centering controls. This requires that the cathode potential be made highly negative and that the intensifier ring be made highly positive with respect to the reference anode or ground. Voltages of the order of 2000 volts or more are used between the cathode and

the intensifier ring, and, consequently, indiscriminate exploring and probing around the inside of a connected oscilloscope is not conducive to happiness and long life. The amplifiers are of the conventional resistance-capacitance type and commonly use twin triodes.

Some oscilloscopes are designed with special features. One of these is a *Z* axis amplifier and control employed to vary the intensity of the beam and the brilliancy of the fluorescent spot in conformity with a modulating signal impressed on the control grid. Since the two pairs of deflecting plates can be used for periodic scanning of the screen by deflection of the beam, in both vertical and horizontal directions, such an instrument finds application in television reception. Intensity control may also be used as a timing agency.

A disadvantage of an ordinary cathode-ray oscilloscope is that it has only one beam or element, whereas electromechanical types have from three to eighteen. By means of the electron switch described in Sec. 3–10, two voltages can be made to deflect the beam in sequence by switching from one circuit to the next, and the persistence of the spot on the screen lends continuity to each trace. Cathode-ray tubes that incorporate two and three separate individual beams have been announced. Some of the advantages of the cathode-ray oscilloscopes are portability, ease of operation, extremely low power requirements from the circuit under test, wide frequency response, and low cost.

4–6. Oscilloscope Applications

Oscilloscope measurements include those of voltage, current, power, phase angle, and time; alternating or recurring waveforms may be observed and unknown frequencies may be determined by comparing them with a known frequency. Mechanical quantities, such as strain, pressure, and vibrations, are easily measured and analyzed. Specialized uses include the rapid testing and determination of the characteristics of electrical equipment.

The oscilloscope may be used as a d-c or a-c voltmeter. A terminal strip, to which the deflecting plates are connected, is mounted at the rear of the instrument, as indicated in Fig. 4–13. The amplifiers respond to frequencies as high as 100,000 cycles

per second in some instances but are incapable of making d-c measurements; these require direct connection of the deflecting plates to the voltage in question. In alternating-voltage measurements, the deflection on the screen indicates the maximum values instead of the effective or root-mean-square values obtained with ordinary a-c voltmeters. Current may be measured by taking the voltage drop across a calibrated resistor. Either

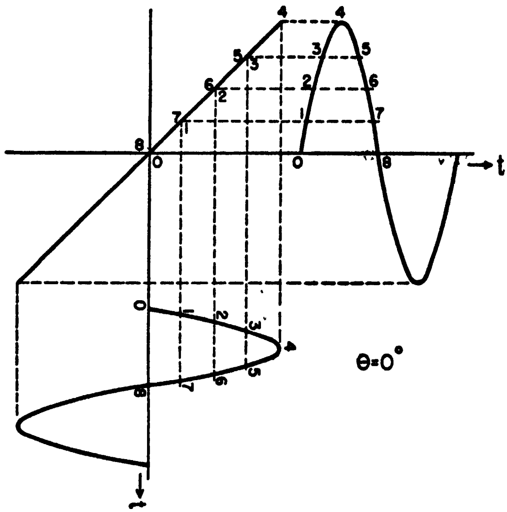


FIG. 4–14. Pattern obtained on an oscilloscope screen when two sine-wave voltages of equal amplitude and same frequency are impressed on the tube. Phase angle = 0°.

voltage or current waveforms may be observed by impressing the properly synchronized voltage from the relaxation oscillator on the remaining pair of deflecting plates.

Comparison of the frequencies and phase-angle displacement between two alternating voltages may be made by connecting one source to the vertical and the other to the horizontal deflecting plates. The traces form the familiar Lissajous figures. If the voltages have the same frequency and are in phase, the trace is a straight line as developed in Fig. 4–14. As the phase angle changes, the trace changes to an ellipse, becomes a circle at a phase displacement of 90° if the voltages have equal amplitudes, develops into an oppositely inclined ellipse, and finally again becomes a straight line when the displacement is 180°.

Between 180° and 360° the image again retraces the patterns, as indicated in Fig. 4–15.

The phase difference between two voltages of the same frequency can be determined by measuring the horizontal intercept and the maximum horizontal deflection as illustrated for the 30° case in Fig. 4–15. The ratio m/n is the sin θ, where θ is the phase angle, as may be seen from the following.

Let the voltage E_V, which is impressed on the vertical deflecting plates, be given by the equation

$$E_V = E \sin 2\pi ft, \tag{4–1}$$

where E is the maximum voltage (vertical), f is the frequency in cycles per second, and t is the time in seconds. Also let the

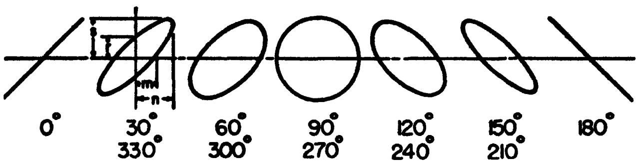


FIG. 4–15. Lissajous figures obtained for various phase angles between two alternating voltages impressed on an oscilloscope. Amplitude ratio 1 : 1. Frequency ratio 1 : 1.

voltage E_H, which differs by the phase angle θ and which is impressed on the horizontal deflecting plates, be given by the expression

$$E_H = E' \sin (2\pi ft + \theta), \tag{4–2}$$

where E' is the maximum voltage (horizontal). At $t = 0$, we have

$$\begin{cases} E_V = 0, \\ E_H = E' \sin \theta. \end{cases} \tag{4–3}$$

Therefore the X intercept is $E' \sin \theta$ or m. The maximum horizontal deflection is E' or n, and so

$$\frac{\text{Horizontal intercept}}{\text{Maximum horizontal deflection}} = \frac{m}{n} = \frac{E' \sin \theta}{E'} = \sin \theta. \tag{4–4}$$

Similarly,

$$\frac{\text{Vertical intercept}}{\text{Maximum vertical deflection}} = \frac{r}{s} = \sin \theta. \tag{4–5}$$

The circular pattern at the two quadrature points can be obtained only if both voltages have equal magnitudes. If they are not equal, the trace consists of an ellipse with its major axis in either a horizontal or vertical direction, depending on the voltage ratio. Sometimes a circular trace is used as a time axis and the signal is impressed on the grid to vary the intensity of the beam. Spiral traces also depend on the use of two voltages in quadrature with both voltages changing gradually in magnitude from zero to a value where the trace moves around the outside

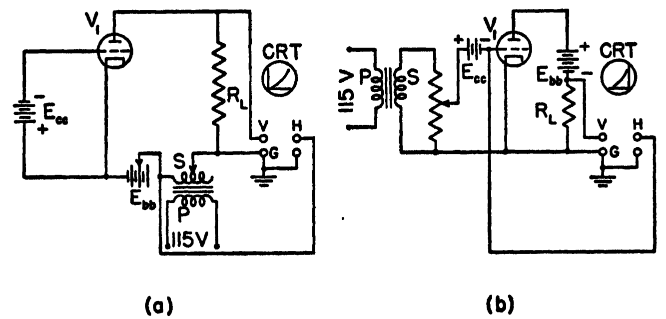


FIG. 4–16. Circuit for observing (*a*) anode characteristic of a vacuum tube; (*b*) grid-anode transfer characteristic of a vacuum tube.

periphery of the screen, after which the voltages are reduced quickly to zero and the process repeats.

When the two alternating voltages are of different frequencies but bear simple ratios to each other, such as 2 to 1, 3 to 2, 5 to 4, etc., the Lissajous figures assume interesting, stationary patterns. One of the rule-of-thumb methods of determining the frequency ratio is to count the number of times a horizontal line is cut by the trace and divide that by the number of times the trace cuts a vertical line.

A simple application of the cathode-ray oscilloscope lies in the determination of vacuum-tube characteristics. The method rests on the fact that, when two sinusoidal waveform voltages of zero phase difference are impressed on the two pairs of deflecting plates of a cathode-ray tube, the line trace produced is inclined at an angle depending on the relative magnitudes of the voltages. The circuit, Fig. 4–16(*a*), used for the determination of anode characteristics, shows a method of placing the alternating voltage, which is applied to the anode of the triode V_1, on the horizontal

deflecting plates, and the voltage drop across the resistor R_L, which varies with the anode current i_b, on the vertical plates of a cathode-ray oscilloscope. The anode battery E_{bb} prevents the anode voltage from going negative; the alternating voltage is adjusted, by means of a multitap transformer, so that the maximum negative voltage is just equal to the battery voltage. Consequently, the anode-voltage range extends from zero to twice the maximum value of the alternating voltage, and the anode current is in phase with the voltage. Both oscilloscope amplifiers are adjusted to locate the resultant curve suitably on the screen, and the values along each of the axes may be graduated if desired. By changing the grid voltage E_{cc}, a family of anode characteristics similar to those given in Fig. 3–5 may be obtained.

A circuit for viewing the grid-anode transfer characteristic is shown in Fig. 4–16(*b*). The alternating voltage on the grid is supplied by a step-down transformer which has a potentiometer connected across the secondary winding. The deflection for the anode current is obtained as in the previous example. A family of curves results when the anode voltage is changed.

When the oscilloscope is calibrated for anode current on the vertical axis and grid voltage on the horizontal axis, the tube resistance, amplification factor, and mutual conductance of the tube may be determined as was shown in Sec. 3–2. The same methods may also be used to determine the characteristics of multielectrode tubes, but it is, of course, necessary that the extra electrodes be supplied with their proper voltages in order to obtain the specific characteristic.

4–7. Radar Fundamentals

In 1922 A. H. Taylor made the observation that some of the energy was reflected back to the radio transmitter when a ship passed between it and the receiver. Subsequent experimentation with reflected radio waves pointed the way toward the solution of the problem of an altimeter for the rapidly expanding air transportation industry, which needed an instrument operable at night, in fog, and at low ceilings to determine the actual height of an airplane above the ground. Still later radio detecting and ranging, abbreviated *radar*, was perfected and used extensively in World War II to detect aircraft, submarines, and

other ships, and served as a very important electronic eye for ships and aircraft.

Early radiotelegraph and radiotelephone work disclosed that ionized layers of air, termed the ionosphere and caused by ultraviolet radiation from the sun, existed at various heights above the earth's surface. These layers, consisting of the E layer at about 75 miles, the F_1 layer at about 125 miles, and the F_2 layer at nearly 200 miles, are responsible for the transmission of long-distance radio signals beyond the earth's curvature by deflecting the radio energy back toward the earth. The ionosphere is higher at night than during the day because the E and F_1 layers disappear after sunset. The reception of long-range radio signals depends on the height of the ionosphere layers, as well as on the frequency of the radio signals. The National Bureau of Standards obtains technical data on the height of these ionized layers by noting the elapsed time between transmitted pulses and the reception of their reflection from these layers; it publishes these data periodically.

As the ultrahigh radio frequencies were developed and utilized, it soon became apparent that these waves were not reflected from the ionosphere but were limited in their reception by the horizon; that is, the transmitting and receiving antennas could not be obscured from each other by the earth's curvature. Nevertheless, ultrahigh frequencies are well suited for accurate radio echo explorations. A modified cathode-ray oscilloscope is the indicating device on which the time intervals between the transmitted signal and its echo are measured in microseconds, or as the distance to the reflecting object, since the speed of electromagnetic waves in space is equal to that of light, that is, approximately 186,000 miles per second or 1 mile in 5.4 microseconds.

A simplified block diagram of a radar transmitter and receiver is shown in Fig. 4–17. The transmitter, supplied with the proper direct voltages from a rectifier, sends out high-frequency pulses controlled by the oscillator in the oscilloscope and a keying unit. Waveforms of the pulses are indicated on lines connecting the various units. Radar systems use pulses that have peak voltages ranging from 5 to 30 kilovolts and peak currents as high as 250 amperes. The pulse frequencies vary from a few hundred up to about 4000 pulses per second, each pulse having a duration

in the range from 0.1 to 6 microseconds. Radar transmitters deliver peak powers between 2 kilowatts and 3000 kilowatts, depending on the distance to be covered and the sharpness of the pulses. However, the average power level is of the order of 0.001 of the peak power because the pulses are of such short duration. Although only low-power tubes are required even in large units, the high peak powers demand that the tubes be

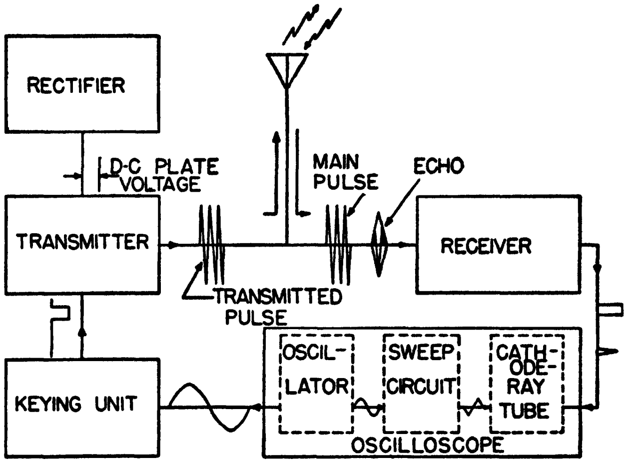


FIG. 4–17. Simplified functional diagram of a radar system. Waveforms of voltages delivered from one block to the next are shown on the connecting lines. *Courtesy United States Signal Corps Engineering Laboratories.*

capable of delivering high electron emission at high anode voltages. The input to the receiver is automatically short-circuited by means of a special tube during the transmission of each high-frequency pulse. Echoes are received on the common antenna between pulses, amplified and rectified in the receiver, and then impressed on the cathode-ray tube of the oscilloscope. An idealized pattern consisting of a miniature trace of the rectified main pulse followed by a trace of the rectified echo is shown on the right-hand line of the figure.

If, as indicated in Fig. 4–18, a directive antenna radiates electromagnetic energy in a beam having a solid angle θ, the power density P per unit area will be

$$P = \frac{P_t}{\theta d^2}, \tag{4-6}$$

where P_t is the radiated power, and d is the distance from the transmitter. If all the energy that strikes a target of area A within the beam is reflected, the reflected power P' is

$$P' = \frac{AP_t}{\theta d^2}. \tag{4-7}$$

The reflecting surface may be considered to have no directive radiating properties, and the reradiated energy may thus be viewed

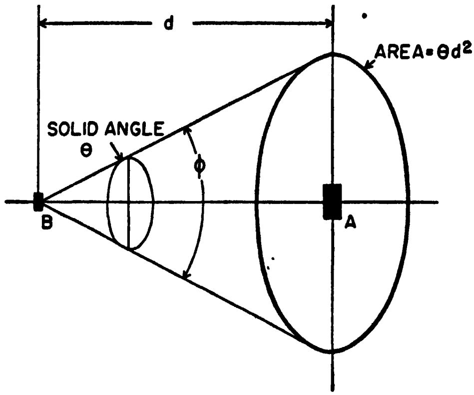


Fig. 4–18. Diagram for determining reflected radio-frequency energy. Transmitting and receiving antenna is indicated at B; target at A.

as a point source for spherical radiation. The receiving antenna of area B will intercept a fraction of the reflected energy equal to the ratio of the antenna area to the area of the spherical envelope, or $B/4\pi d^2$. The received power P_r is, therefore,

$$P_r = \frac{BAP_t}{4\pi\theta d^4}. \tag{4-8}$$

The relationship between a solid angle of revolution θ and a plane angle ϕ is

$$\theta = \frac{\pi\phi^2}{4}. \tag{4-9}$$

Consequently, the received power in terms of the plane angle is

$$P_r = \frac{BAP_t}{\pi^2\phi^2 d^4}. \tag{4-10}$$

In a conventional broadcast system, a receiving antenna re-

ceives power P_r' throughout 4π radians, and

$$P_r' = \frac{BP_t}{4\pi d^2}, \tag{4-11}$$

where B is the area of the receiving antenna, P_t is the radiated

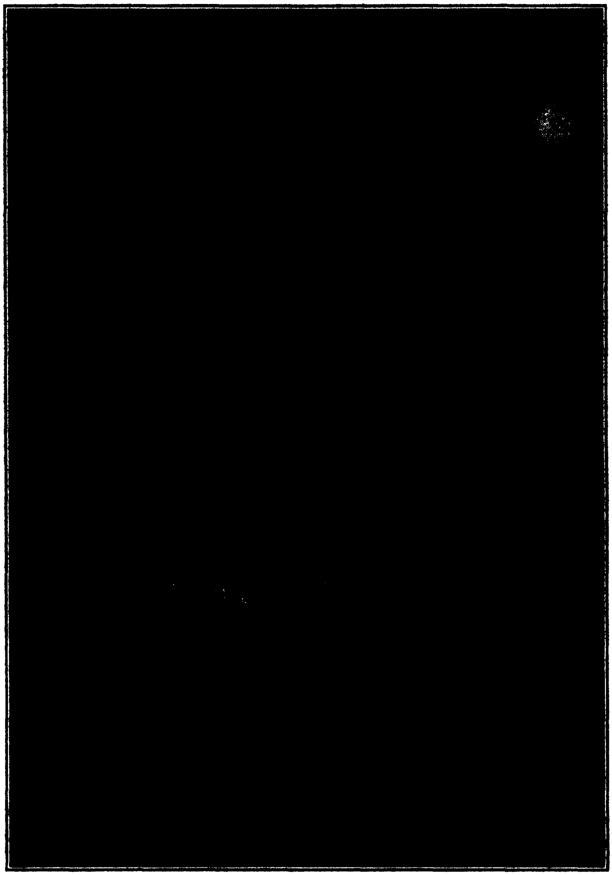


FIG. 4-19. Antenna used to establish radar contact with the moon. *Courtesy United States Signal Corps Engineering Laboratories.*

power, and d is the distance between the transmitter and the receiver. The ratio of the power received in a broadcast to that in a radar case is

$$\frac{P_r'}{P_r} = \frac{\pi\phi^2 d^2}{4A}. \tag{4-12}$$

This shows that the received radar power is only a very small fraction of that received from an ordinary broadcast station for the same transmitted power, and, therefore, transmitters capable of delivering large power pulses and extremely sensitive receivers must be employed in radar installations.

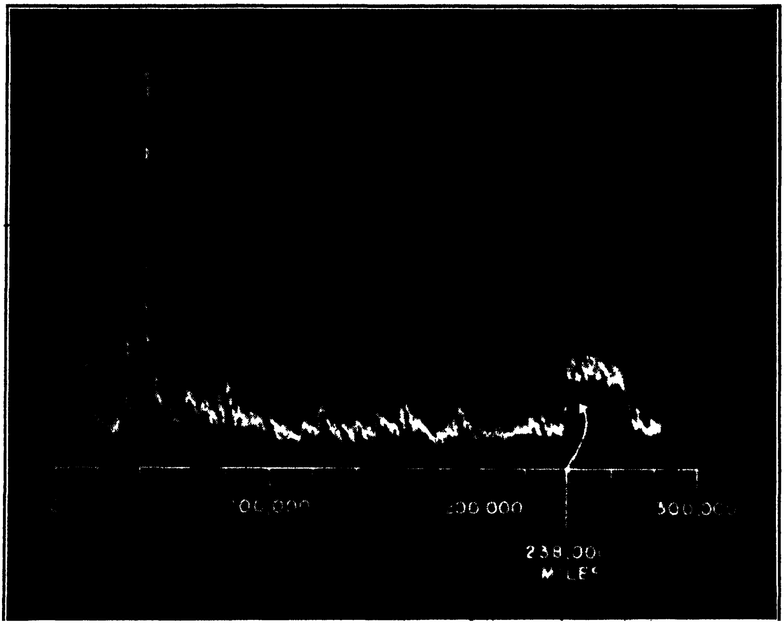


FIG. 4–20. Photograph of a radar pulse and its echo from the moon as seen on the radar oscilloscope. Moonrise 1-22-46. Azimuth 89°. Velocity +682 mph. *Courtesy United Signal Corps Engineering Laboratories.*

In 1946 the United States Signal Corps announced that its laboratory in New Jersey had established radar contact with the moon, which is located about 238,850 miles from the earth. The Signal Corps antenna, illustrated in Fig. 4–19, consisted of 64 dipole units with reflectors mounted on a 100-foot tower. The transmitter operated on a frequency of 111.6 megacycles and radiated a 0.25-microsecond pulse of about 3-kilowatt peak power every 4 seconds. Calculations had indicated that only about 16 per cent, or 3 watts, of the impinging energy would be reradiated because of absorption, and consequently the receiver design was very complex; its sensitivity had to be several hundred

times that of a high-quality radiobroadcast receiver. A copy of the oscillographic record showing the main pulsé and the echo, received about 2.4 seconds later, is given in Fig. 4-20. This record is typical of the images obtained with radar equipment of this kind. Other types will be described in Chapter 9.

4-8. Electron Microscope

The resolving power, that is, the ability to produce separated images of two points which lie close together, of an optical microscope is given by the equation

$$d = \frac{0.61\lambda}{\mu \sin \alpha}, \tag{4-13}$$

where d is the distance between the two points and λ is the wavelength of the illuminating radiation, both in similar units; μ is the index of refraction of the medium in which the object is located; and α is the angle subtended at the object by the radius of the microscope's aperture.

The refractive index μ of all known transparent materials is not greater than 1.7, and since $\sin \alpha$ is limited to a maximum value of 1, the solution for increased resolving power lies only in reducing the wavelength λ. For the best microscopes and using ultraviolet radiation for illumination, the maximum magnifying power is limited to about 2000 times; any further photographic enlargement beyond this shows no new detail but simply enlarges the picture. The limiting resolution under the optimum conditions is approximately 1000 angstrom units.

In 1924 L. de Broglie proposed a wave theory of moving particles of atomic dimensions and deduced the important relationship

$$\lambda = \frac{h}{mv}, \tag{4-14}$$

where λ is the wavelength in meters of the wave, h is Planck's radiation constant (6.624×10^{-34} joule second), m is the mass in kilograms of the particle, and v is the velocity in meters per second of the particle. With a beam of electrons, this equation may be written more simply in the form

$$\lambda = \sqrt{\frac{150}{V}}, \tag{4-15}$$

where λ is the wavelength in angstrom units and V is the potential drop in volts through which the electrons pass.

De Broglie's theory has been verified in experiments that yield accuracies to within 0.3 per cent. From these the deduction is inevitable that in some manner moving electrons act as a wave motion and have a wavelength, while at the same time they retain their identity as a stream of particles. A moving beam of electrons, accelerated by a voltage of 50 kilovolts, for example, has a wavelength of approximately 0.055 angstrom unit. This is of the order of 0.000,01 of the wavelengths of visible light; therefore, the resolving power has been greatly increased, and enormously larger and more useful magnifications have become possible.

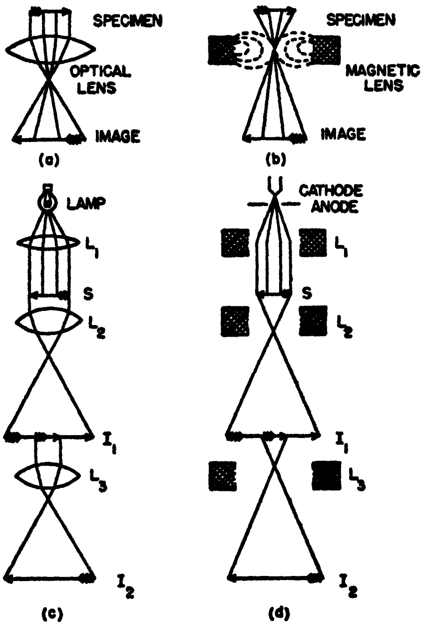


FIG. 4-21. (*a*) Relation of specimen and image in a simple optical system; (*b*) analogous action of a doughnut-shaped coil on an electron beam; (*c*) basic principle of the light microscope; (*d*) basic principle of the electron microscope. *Courtesy Radio Corporation of America.*

An electron microscope utilizes the electron gun and the fluorescent screen of the cathode-ray tube as foundation elements. The equivalent of glass lenses in an optical microscope is achieved by either electric or magnetic fields which focus the electron beam. In 1940 V. K. Zworykin and his associates developed a small, compact, and easily operable commercial instrument which yields magnifications for direct viewing as great as 20,000 times. By photographic enlargements, discernible details may still be seen at magnifications as high as 100,000 diameters.

The similarity between a transmission-type light microscope and the electron microscope is shown in Fig. 4-21. In dia-

gram *c*, the light rays from a lamp pass through the condenser lens L_1 where they are formed into a parallel beam and directed on the specimen *S*. The image of the specimen falls on the objective lens L_2 which focuses and produces a magnified image I_1.

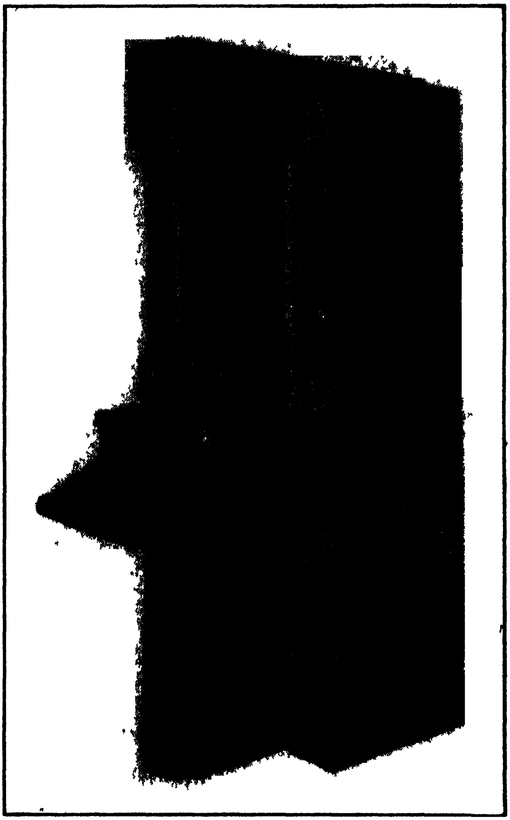


FIG. 4–22. Universal model electron microscope. Height, 75 inches; width, 24 inches; depth, 42 inches. *Courtesy Radio Corporation of America.*

A portion of this enlarged image is magnified by the projector lens L_3, and the eye sees the doubly enlarged shadow image I_2 on an observation screen. In the electron microscope, diagram *d*, the hot cathode emits electrons, which are accelerated by the anode potential and formed into a parallel beam by the magnetic field of the doughnut-shaped coil L_1 or equivalent *magnetic lens*. The electron beam in passing through the specimen is affected in varying degrees by the density of the specimen. Electrons

passing through it are acted on by the magnetic field of coil L_2 and form an enlarged image I_1. A section of this image is magnified by a third field to form the shadow image I_2 which is

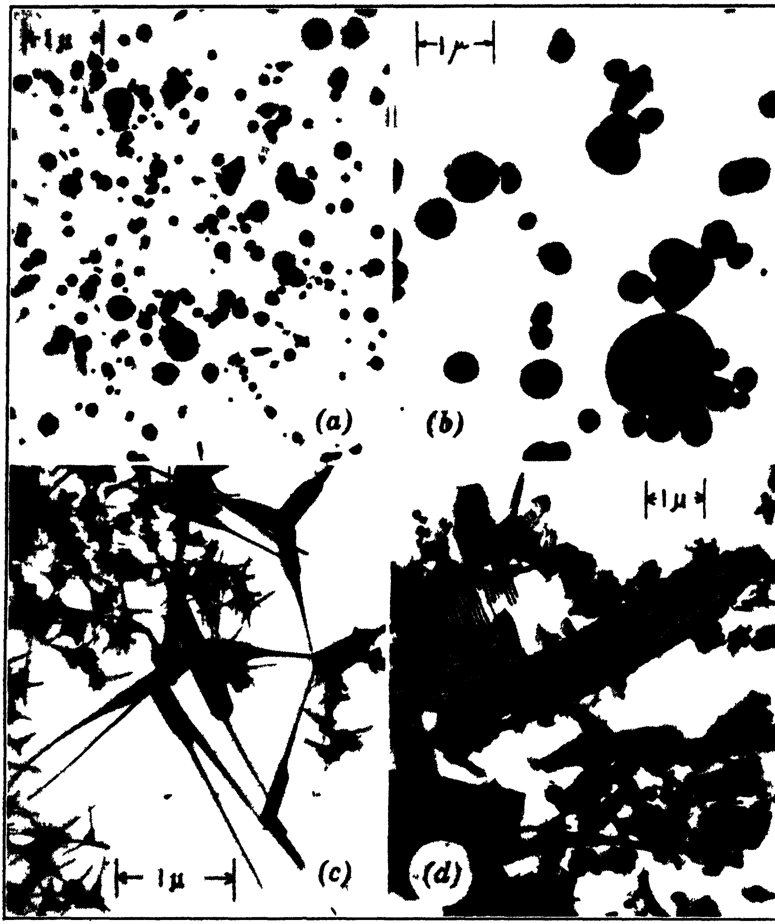


FIG 4–23 Electron microscope photographs of (*a*) fly ash; (*b*) carbon black; (*c*) zinc oxide; (*d*) diatomaceous earth. *Courtesy Illinois Institute of Technology.*

made visible by means of a fluorescent screen or by the exposure of a photographic plate.

In the upright universal model, Fig. 4–22, the microscope column, the oil-diffusion pump which produces and maintains an

operating vacuum of about 10^{-6} millimeter of mercury pressure, and the highly regulated 50-kilovolt anode power supply are built into the cabinet. The mechanical, first-stage vacuum pump and voltage regulator are separate and may be located in another room. The electron gun is located at the top of the column, and the specimen chamber is just beneath it. The specimen is made very thin and is usually mounted on a 200-mesh screen. An observer views the image through glass ports just above the control board. These ports are covered with a sliding shield when a photograph is made. Meters on the control panel indicate air pressure and are used in maintenance; the knobs are used to move the stage and control the focus, magnification, and brilliance. By changing the potential on the anode and the current through the three magnetic coils, the magnification can be adjusted to any value between 100 and 20,000 times.

Electron microscopes of either the universal or the smaller console types find application in such fields of science and industry as the determination of particle size, analysis of materials, study of molecular structure, and behavior of bacteria and viruses. A number of typical photographs taken from 2 inch by 2 inch exposures are shown in Fig. 4–23.

4–9. Electron Diffraction

In 1927 de Broglie's wave theory of moving electrons received startling confirmation by C. J. Davisson and L. H. Germer. They showed that beams of electrons are diffracted by a nickel crystal and that the wavelengths, as deduced from the diffraction patterns for electron beams of various speeds, agree with his equation (Eq. 4–14). In their experimental arrangement, electrons were emitted by a hot cathode, and then accelerated, and formed into a beam directed at a known angle of incidence against the face of a nickel target. The interplanar spacing of the lattice of atoms acted as a diffraction grating, and some of the electrons, on striking these atomic facets, were reflected without loss of energy; their distribution was determined by explorations with a Faraday collector. Reflection of the electron beam took place only under the conditions given by Bragg's law, which may be written

$$\lambda = \frac{2d \sin \theta}{n}, \qquad (4\text{–}16)$$

where λ is the wavelength in angstrom units of the electron beam, d is the distance in angstrom units between the atomic planes, θ is the angle between the beam axis and the atomic planes, and n is a small integer that designates the order of the reflection.

The wavelength of the electron beam is about that of X rays, that is, small compared with the linear dimensions of the reflecting surface. The reflected beam is composed of a large number of scattered waves that spread out from the regularly arranged layers of atoms which are parallel to the surface of the crystal. Emerging rays will reinforce, that is, be in phase, if the angle of incidence of the beam is such that the length of path of two reflected rays differs by a whole number of wavelengths. If the length of path differs by 1 wavelength, we have the first-order reflection ($n = 1$). At a larger angle θ, the path difference will be exactly 2λ, and the second-order reflection ($n = 2$) occurs. Each diffraction beam is characterized by a definite wavelength, and that particular beam is present in the pattern if it contains radiation of that wavelength or some submultiple value of that wavelength, but not otherwise. If the incident electron beam is monochromatic, that is, if a single wavelength is obtained by holding the accelerating voltage extremely constant, no diffraction beams occur until the wavelength coincides with a wavelength of one of the reflected beams.

Diffraction beams issue not only from the incidence side but also from the far side of the crystal along with the transmitted beam. Patterns of this type were obtained first by G. P. Thomson in 1927. In the transmission method, a thin film or a mass of finely divided crystals is placed in the path of the beam; a photographic plate, normal to the beam and beyond the specimen, receives and records the radiation. Even though the crystals are arranged at random, the pattern is the same as that produced by a single crystal turned into the same random positions. Of these various spacings, one is unique in giving rise to the first-order diffraction spot; another produces the second-order spot, and so forth. By rotating the specimen about the primary beam, these spots generate a ring pattern, which may be analyzed for crystal and wave information.

The electron microscope, Fig. 4–22, is equipped with an electron-diffraction camera. A diffraction pattern of a specimen is obtained by inserting it in the lower chamber, shown to the right

and above the viewing chamber. Photographs of two transmission-type patterns are given in Fig. 4–24. Diffraction-pattern analyses clarify many problems regarding surface layers of crystalline structures and their changes with treatment. In the reflection method the incident electron beam penetrates no deeper than about 20 angstrom units, and the patterns disclose

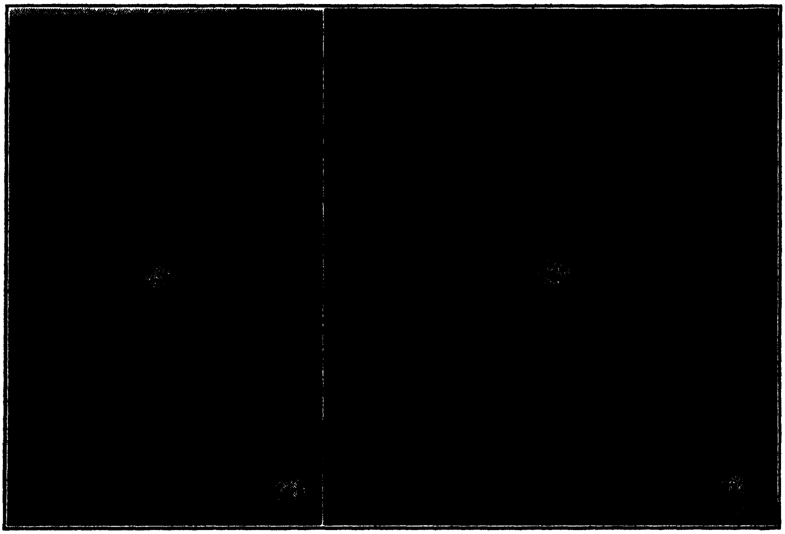


Fig. 4–24. (*a*) Single crystal diffraction pattern of a very thin mica film; note netlike arrangement of spots in three parallel lines at 60° to each other. (*b*) Ring diffraction pattern of manganese dioxide. *Courtesy Illinois Institute of Technology.*

conditions in the outside surface layers. One of the many achievements concerns wear in gasoline-engine cylinders. Aluminum pistons cause excessive wear because the amorphous aluminum oxide films formed during running recrystallize as the abrasive sapphire when the engine stops. When the engine is started, this layer causes cylinder wear for an appreciable time until the amorphous layer caused by the polishing action again re-forms. This abnormal wear is eliminated by alloying the aluminum with magnesium so that a spinel is formed as an oxide film. The part played by electron diffraction in predicting and confirming these results has led to amazing improvement in engine performances. Electron diffraction has also been utilized

to control the running-in of bearings by applying only light loads until the bearing surface forms an amorphous layer, in the analysis of oxide films formed during heat treatment, and in the solution of similar problems.

4–10. Electron-ray Tube

In 1935 R. M. Wagner developed the *electron-ray tube,* also termed the Magic Eye, which indicates resonance in a radio receiver for proper tuning and can be used as a voltmeter or

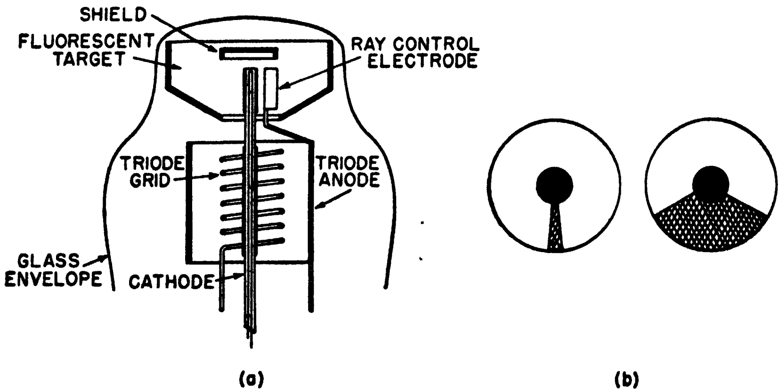


FIG. 4–25. (*a*) Cross section of the electrodes in an electron-ray tube; (*b*) limiting shadow patterns obtained with zero and maximum negative voltages on the control electrode of an electron-ray tube.

galvanometer. The internal structure of the tube, shown in cross section in Fig. 4–25(*a*), consists of two portions, a triode and a simplified cathode-ray tube. Both portions use a common indirectly heated cathode, but the emissive coating is applied only to the surface located within the grid of the triode and that part of the cathode which is located within the conical portion of the fluorescent screen. A control electrode, consisting of a thin strip of metal welded to the upper portion of the triode anode, is located between the cathode and the metal target but touches neither.

When a positive voltage equal to that on the target is applied to the control electrode, the entire inside conical portion of the target fluoresces. If, however, the control electrode is at a lower positive potential, which in effect means that its potential is negative with respect to the target, the electrons from the cathode

are repelled to an extent depending on the magnitude of the potential difference; they fail to reach the target throughout that sector; and a corresponding shadow results. The end view of the target for these two limiting values is shown in Fig. 4–25(*b*). A cap, located above the cathode and supported by the target, confines the electrons to the conical portion and serves as an electrostatic shield to prevent spurious indications.

A simple circuit incorporating the electron-ray tube is given in Fig. 4–26. The symbol for the tube V shows the triode portion at the left and the indicator portion at the right; the triode anode is extended to show the control electrode between the common cathode and the target. The anode supply voltage is connected to the target, and a resistor R_1, having a value between $\frac{1}{2}$ and 2 megohms, is connected between the target and the anode. If the triode grid is sufficiently negative, no anode current flows, both anode and target are at the same potential, and the fluorescence on the target extends practically throughout 360°. When the grid potential of the triode is made less negative, anode current flows and a corresponding voltage drop exists across resistor R_1. This results in a lower anode potential than that impressed on the target, and a shadow depending on the magnitude of the anode current appears. The average control characteristics of a specific electron-ray tube are shown in Fig. 4–27. The circuit also shows a grid resistor R_2 and a capacitor C. These introduce a time constant R_2C in the operation of the tube; by a suitable choice of their values, the indicator may be made to respond more or less rapidly.

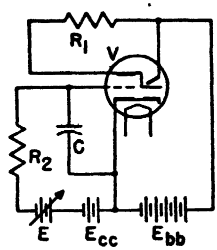


FIG. 4–26. Simple circuit for an electron-ray tube.

The variable direct voltage E which causes the shadow is connected in the circuit so that an increased negative voltage will result in a decreased shadow angle; however, the shadow action may be reversed by reversing the polarity of the voltage E. In that case, an increased voltage causes the triode grid to become less negative, the triode anode current increases, and this in turn produces an increased shadow angle. When the electron-ray tube is used as a resonance or tuning indicator in a radio receiver, the detector, which rectifies the high-frequency carrier,

impresses a portion of the rectified carrier voltage across a resistor connected in the triode grid circuit. The magnitude of the minimum shadow angle affords an index of the strength of the received signal, and resonance or precise tuning is obtained by adjusting the radio receiver for that minimum.

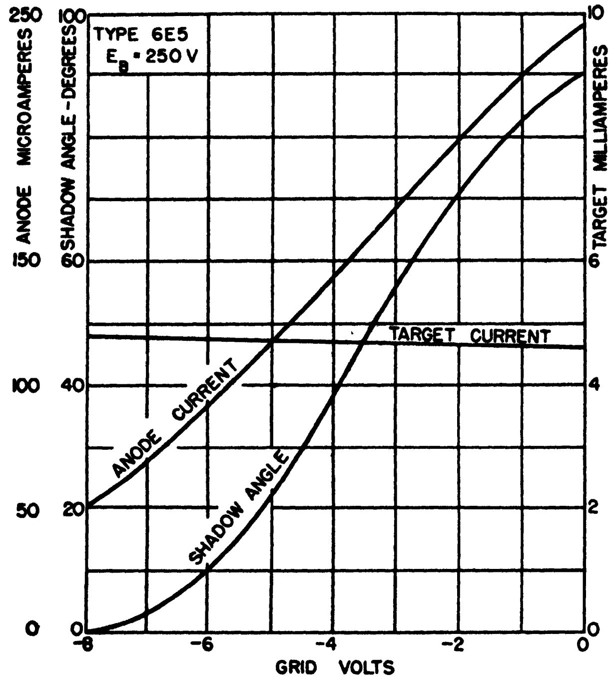


FIG. 4–27. Operating characteristics of a typical electron-ray tube.

4–11. Resistance-capacitance Wheatstone Bridge

The electron-ray tube is frequently applied as a visual balance or null indicator for test or production equipment. A circuit diagram of a bridge which may be used to measure either resistance or capacitance is shown in Fig. 4–28. The unknown is connected to the appropriate terminals, R_X or C_X; the standards are the resistors R_1 to R_4 and the capacitors C_1 to C_3. The slide wire consists of an adjustable potentiometer R_5, flanked by the extension resistors R_6 and R_7. A low alternating voltage is applied to the bridge through the current-limiting resistor R_8. If R_6 and R_7 are assumed to have zero resistance, the potentiometer

slider may be moved to a position where there is no difference of potential between that point and the junction of the standard and the unknown. At that position, the value R_X in ohms of an unknown resistor is given by the equation

$$R_X = R_S \frac{R_R}{R_L}, \tag{4-17}$$

where R_S is the resistance in ohms of the standard resistor, R_R is

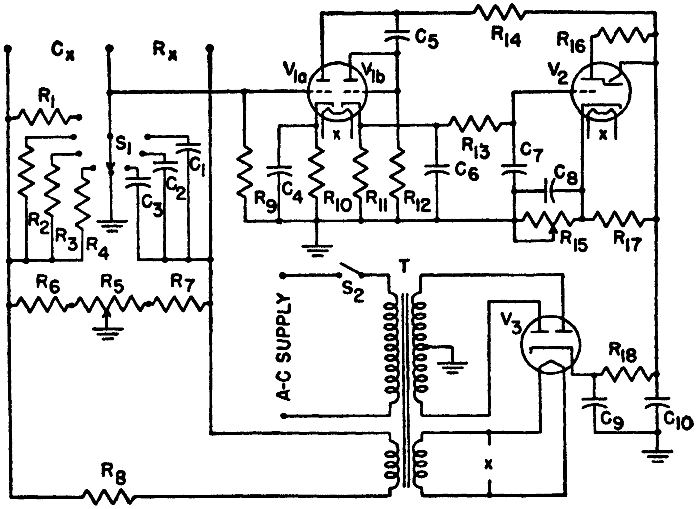


FIG. 4-28. Circuit of a resistance-capacitance Wheatstone bridge with an electron-ray tube as an indicator.

the resistance in ohms in the bridge arm to the right of the slider, and R_L is the resistance in ohms in the bridge arm to the left of the slider.

When the bridge is used to measure capacitance, the value C_X in microfarads of the unknown capacitor is

$$C_X = C_S \frac{R_L}{R_R}, \tag{4-18}$$

where C_S is the capacitance in microfarads of the standard capacitor, and R_S and R_L have the previously assigned designations. The reactance in ohms of a capacitor is given by the expression $1/2\pi fC$, where f is the frequency and C is the capacitance; this accounts for the inverted resistance ratio in Eq. 4-18.

Resistors R_6 and R_7 usually have the same resistance, which is generally equal to $0.1R_5$. They are added to increase the sensitivity of the bridge; their effect is equivalent to lengthening the slide wire. During operation of the bridge, any unbalance voltage is impressed in the grid circuit of the first section V_{1a} of a twin triode, amplified, and then rectified by the second section V_{1b} which is operated as a diode. The resulting direct voltage appears across a very high resistance R_{11} in the cathode circuit of the second section. Capacitor C_6 has such a value that the time constant of the circuit produces no noticeable time lag between a dial adjustment and the indicator-tube response. The resistor R_{15} provides the grid bias for the electron-ray tube V_2 and is adjusted so that the shadow angle is at the most sensitive position; that is, it covers zero degrees. Additional current from the high-voltage source flows through R_{15} and R_{17} and aids in setting the adjustment, which is made with the switch S_1 in the adjusting position, as shown in the figure, and which remains the same for all scales.

A general-purpose instrument may be equipped with standard resistors having values of 1 ohm for R_1, 100 ohms for R_2, 10,000 ohms for R_3, and 1 megohm for R_4, and standard capacitors of values 1.0 microfarad for C_1, 10,000 micromicrofarads for C_2, and 100 micromicrofarads for C_3. The instrument, when calibrated, has a scale that is approximately logarithmic and that reads from 0.1 to 10. After the preliminary adjustment of the shadow angle, the switch is connected to a suitable measuring position and the main dial is varied until a minimum shadow angle is obtained. At that point the product of the standard value, as indicated by the switch position, and the reading on the main dial is the value of the unknown resistance or capacitance. Leakage in a capacitor may also be estimated by observing the minimum shadow angle at balance. A bridge of this type is constructed easily and is frequently found in radio service stations.

4-12. Mixer and Converter Tubes

Multigrid tubes are constructed with additional grids between the cathode and the anode aside from those in an ordinary pentode. If a varying voltage is impressed between such an additional grid and the cathode, the grid acts as an independent con-

trol grid. Double control or mixing is used in carrier-current and radiobroadcast receivers of the superheterodyne type. The modulated high-frequency signal can be amplified more easily and greater stability can be obtained if a local oscillator is used in the receiver to change the signal carrier to one of lower frequency. Instead of tuning each individual amplifier stage, only the input circuit or one stage is tuned to the desired frequency. A local oscillator is tuned simultaneously and de-

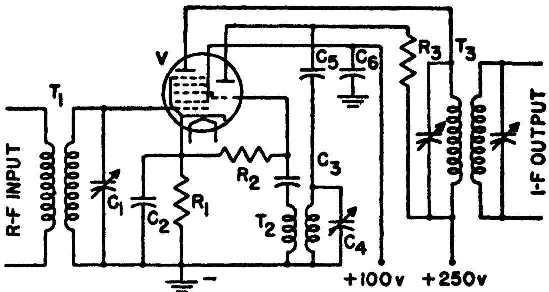


FIG. 4–29. Circuit of a triode-heptode frequency converter. Triode section is used as an oscillator with tuning in anode circuit; heptode section is used as a mixer.

livers a constant amplitude voltage to either the grid or the anode circuit of a *converter* or *mixer tube.* The output of this tube contains the original signal carrier frequency, the local oscillator frequency, the sum and difference frequencies, and the audio frequencies that modulate the carrier frequency. Tuning of the local oscillator throughout the frequency band is arranged so that the difference frequency remains constant and, consequently, two or more fixed *intermediate-frequency* amplifiers are used before the final demodulator or detector. The tuned-anode circuit of the converter is arranged to resonate at the intermediate frequency; it rejects or bypasses the other three high frequencies.

The receiver circuit may be simplified by combining a triode oscillator with the mixer in the same tube. Improved efficiency and simplicity are secured by putting an additional grid, termed the *injector grid,* in the mixer section and connecting that grid directly to the grid of the oscillator section within the tube, as shown in Fig. 4–29. This arrangement permits both the mixer

control grid and the injector grid to control the electron stream and is known as *electron coupling*. The composite tube, termed a *triode-heptode,* has a common cathode with the triode mounted above the heptode section. The screen grid, which shields the injector grid and serves the same purpose as in the screen-grid tube, consists of two internally connected portions with the injector grid located between them; control and suppressor grids are located in their standard positions. The addition of the injector grid introduces a new tube factor analogous to the

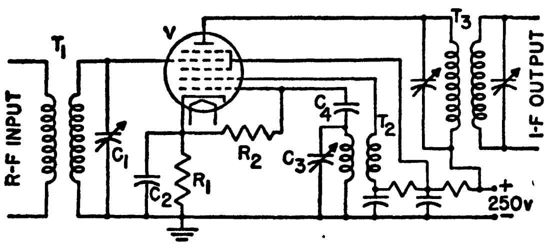


FIG. 4–30. Circuit of a pentagrid converter. Grid circuit tuning is employed in the oscillator portion.

transconductance factor in a triode. This factor, termed *conversion transconductance* and expressed in micromhos, is defined as the ratio of the intermediate-frequency component of the output current of the converter tube to the high-frequency component of the input-signal voltage applied to the control grid.

The action of this combined oscillator and mixer tube may also be realized in a single structure, the *pentagrid converter,* which has five grids in addition to the cathode and the anode. This tube combines the functions of oscillator, mixer, and amplifier within one structure. The simplified circuit of Fig. 4–30 shows that grids 1 and 2 are used as the oscillator grid and anode, respectively. Emitted electrons, after passing through these two grids, are further influenced by the control grid 4, which is shielded from the oscillator anode by the screen grid 3 and from the main anode by the screen grid 5. The two screen grids are connected together within the tube. In the construction of one form of the tube, grid 1 surrounds the cathode, but grid 2, which is used as the oscillator anode, actually consists of a pair of side rods but no grid wires are attached to them. Many of the electrons approaching these rods possess sufficiently high

velocities so that they move beyond the equivalent oscillator anode; the majority pass through the screen grid 3 and approach the negatively charged grid 4, which retards the oncoming electron stream. The concentration of electrons between grids 3 and 4 constitutes a virtual cathode for the tetrode or equivalent screen-grid portion of the tube. If grid 1 has a zero potential or is only slightly negative or positive, the virtual cathode has an ample electron supply for the tetrode portion of the tube. Whenever grid 1 assumes a more negative potential, as it does when it functions as the oscillator grid, the number of electrons arriving at the main anode is temporarily reduced. Consequently, current pulsations at oscillator frequency are supplied to the tetrode portion, and the electron stream to the main anode is modulated in addition by the high-frequency signal voltage on grid 4. The main anode current, similar to that in the previously described tube, contains the desired intermediate frequency, the other three high frequencies, and the low frequencies that modulate the carrier.

The bias for the control grid is partially obtained from the voltage drop across a resistor in the detector diode circuit and varies, of course, with the strength of the received signal. By impressing this variable grid bias on the control grid of the converter as well as on the grids of the other radio-frequency amplifying tubes, we obtain an automatic adjustment of the gain, that is, *automatic volume control.* This eliminates variation of the receiver output even though the received signal fades and prevents blasting or overloading from strong local stations during tuning.

Since converter tubes combine the function of an oscillator, mixer, and amplifier in a single tube, they find extensive application in automobile and midget-type radio receivers. They are also used where dual grid control is important, as in multivibrator circuits to obtain frequency division and in phonograph amplifiers to modify the frequency response characteristic.

Problems

1. A tube manual gives the following characteristics of a screen-grid tube: anode voltage 250; screen-grid voltage 90; control-grid bias −3 volts; anode current 4 milliamperes; screen-grid current 1.7 milliamperes; plate resistance 600,000 ohms; transconductance 1050 micromhos. What is the

amplification constant at these operating values? How much power must be dissipated by the screen grid?

2. The screen-grid tube described in Problem 1 is used in the circuit shown in Fig. 4–2. The load resistor in the anode circuit has a resistance of 17,500 ohms. What must be the resistance of the cathode resistor in order to obtain the correct control-grid bias?

3. A cathode-ray tube is operated with −1150 volts on the cathode and +1500 volts on the intensifier ring. Other electrodes are at zero or ground potential. The distance between the cathode and the center of the screen is 16 inches. With what velocity do electrons strike the fluorescent screen?

4. A 110-volt 60-cycle supply line is connected to the vertical, and a 5-volt 180-cycle third harmonic is connected to the horizontal, deflection terminals of a cathode-ray oscilloscope. Both amplifiers are adjusted so that each maximum deflection is 2 inches long. Plot the trace that appears on the screen if: (*a*) the voltages are in phase at the beginning of any cycle; (*b*) the 60-cycle fundamental voltage leads the 180-cycle harmonic by 60° or $\frac{1}{360}$ second.

5. In determining the anode characteristic of a triode by means of a cathode-ray oscilloscope, as shown in Fig. 4–16, two tests are made using (1) an alternating voltage and a battery in the anode circuit, and (2) an unfiltered output voltage of a full-wave rectifier. The alternating voltage is adjusted so as to reduce the total anode voltage to zero at the end of each cycle, and the maximum anode voltage is made the same in both tests. (*a*) Draw the variations of the total applied anode voltage with respect to time for both cases. (*b*) Why or why not is the anode characteristic of the tube as shown on the screen the same for both tests?

6. A radar antenna covering an area of 40 square feet delivers a radio beam through a plane angle of $\pi/12$ or 15°. The energy is reflected from a target 60 miles away. What is the ratio of received power to that received from a broadcast transmitter of the same average power?

7. The grid and anode of the second section V_{1b} of the twin triode, shown in Fig. 4–28, are not directly connected to the d-c power supply. Trace the amplified signal through the first section V_{1a} of the twin triode, and show in detail how the rectified signal voltage to operate the electron-ray tube V_2 is obtained.

8. Why cannot the Wheatstone bridge described in Sec. 4–11 be used to measure accurately the resistance of iron-cored choke or transformer coils?

9. Assume that the potentiometer R_5 in Fig. 4–28 is a uniformly wound 800-ohm potentiometer and that a fixed resistor of 800 ohms is connected from the slider to the point where R_5 joins R_7. Remembering that the resistance of two resistors in parallel is equal to the product of the individual resistances divided by their sum, plot the curve showing the variation of the resistance between the slider and the junction of R_5 and R_7 against percentage of slider rotation.

10. In the pentagrid converter circuit, Fig. 4–30, no bias voltage is shown on the oscillator grid. For proper operation the average negative

voltage on the oscillator grid is as much as 30 to 40 volts, and the maximum instantaneous negative voltage may be 60 to 80 volts Describe in detail how the oscillator grid receives its bias when the tube is first energized and how the proper grid bias is maintained.

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5 ·

Special-purpose Vacuum Tubes

There has been a great demand during recent years for tubes capable of generating ultrahigh frequencies for use in radio communication, television, and radar equipment. This need has been met by the development of tubes that incorporate changes in structural design and by others that utilize new principles of operation. We shall review some of these types and shall also consider several other tubes that have been designed for specific but very important purposes. Moreover, we shall find that some of the special-purpose tubes utilize novel and interesting methods of circumventing basic limitations, while others, such as X-ray tubes, which extend man's vision, and cyclotrons, which transmute elements, are an important part of our modern world.

5–1. Disc-seal Tubes

The high-frequency response of the previously described tubes and circuits is limited on the one hand by interelectrode and parasitic capacitances, and on the other by inductances of the leads from the electrodes to the tube terminals and the connections to the resonant circuits. It is apparent that the leads in the lower portion of the tube and the terminals, molded in glass, act as the plates of a capacitor, and consequently an ordinary triode has an appreciable capacitance between the leads that connect the electrodes to the circuit, aside from the interelectrode capacitances. The grid connection at the side of the triode, shown in Fig. 3–1, is arranged to reduce capacitance between the grid and the cathode leads and thus increases the frequency response of the tube. Further steps in this direction lie clearly

in the reduction of the size of the electrodes within the tube and in the elimination of long leads from the tube electrodes to the resonant circuits.

The triode shown in the cutaway view of Fig. 5-1 is of the external anode type and is arranged for forced-air cooling. It is designed with a coaxial filament stem and a grid structure which terminates in a ring-type grid seal that allows the tube to be seated in direct contact with the chassis or mounting. Single-turn inductors serve as the external portions of the resonant circuits and are combined with the tube in a single unified structure instead of being separate. Ring-type grid-seal tubes deliver an output of several kilowatts at a frequency of 110 megacycles per second, whereas ordinary triodes can be operated to produce full power at frequencies only as high as 50 megacycles per second and at slightly higher frequencies if the maximum values of anode voltage and power input are reduced.

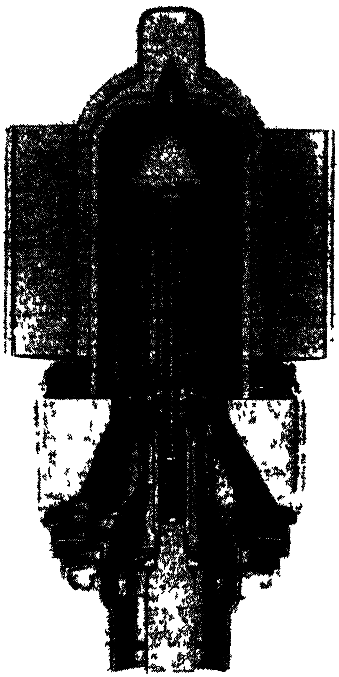


FIG. 5-1. Cutaway view of a ring-type grid-seal triode. Over-all length, 9 inches; diameter, 4.25 inches. *Courtesy Eitel McCullough, Inc.*

The *disc-seal tube* is a further improvement on the basic idea of combining the tube and the circuit. This tube may be described by considering first the simple resonator shown in the upper portion of Fig. 5-2. The cross section shows a cylindrical cavity fitted with a solid metal stud through the center and separated from the lower electrode by a small air gap. The stud is the anode, and the lower electrode is the grid. Multiple spring contact fingers complete the circuit between the metallic discs that form the ends of a glass cylinder

and the separate, external portion of the cavity. All surfaces are silver plated to insure low electrical losses and good circuit contacts. The two opposing surfaces, the anode and the grid, act as a capacitor, and the surrounding metal wall acts as a single-turn inductor. At a certain frequency this single-turn, completely inclosed, resonant cavity is identical to a parallel resonant circuit if a variable-frequency voltage is con-

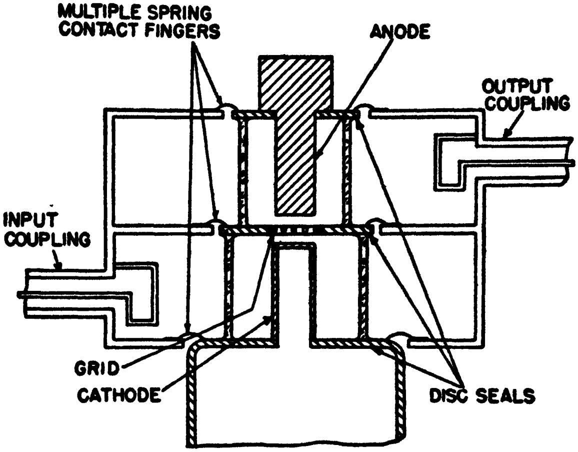


Fig. 5–2. Grid-to-anode and grid-to-cathode cavities with the essential outline of the lighthouse tube.

nected to the two surfaces of the air gap. The changing electric field is concentrated between the two surfaces at the axis and decreases uniformly to zero at the periphery of the cavity. The changing magnetic field is also confined to the cavity, and consequently the structure is completely shielded. Energy is extracted from the cavity by means of a coupling loop and a transmission line.

In the lighthouse tube, shown in cross section in Fig. 5–3, one such cavity is the grid-to-anode section, and another, similar, inverted cavity is used as the grid-to-cathode section. The former is placed above the latter to form a double resonator. A portion of each cavity is made a part of the tube with a metal-to-glass seal. Each cavity is equipped with a coupling loop, connected to a transmission line, by means of which energy from the output circuit may be returned to the input circuit if feedback is desired or if the tube is to act as an oscillator.

The cathode, grid, and anode are placed in close proximity, and hence the transit time of the electrons is extremely short. The grid, located between a flat cathode and the anode, consists of a woven mesh of very fine tungsten wires brazed to a cup, which is deformed during construction to stress the wires to a

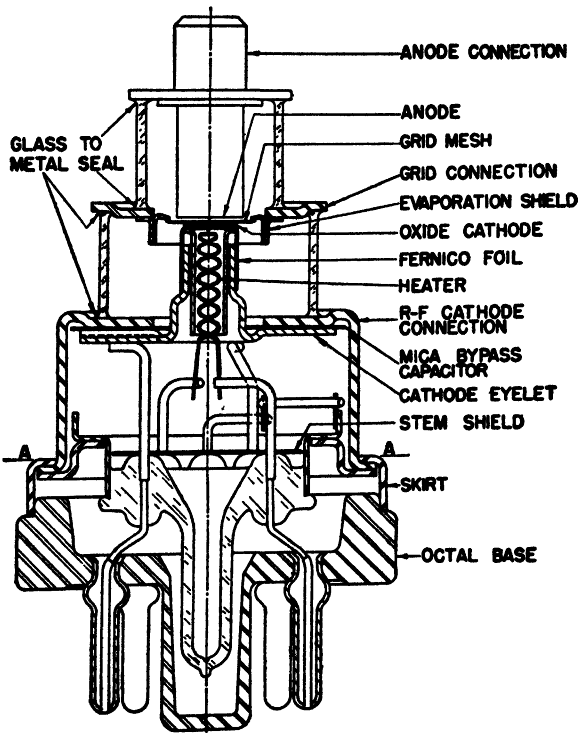


FIG. 5-3. Cross-sectional drawing of a typical lighthouse tube. *Courtesy General Electric Company.*

plane surface and to keep them taut at the processing and operating temperatures. Power-supply connections are made through the base of the tube, which fits a standard octal socket. A mica bypass capacitor is built in as a part of the tube and is used for the isolation of the direct voltage on the grid.

A cutaway view of a small triode of the lighthouse type is shown in Fig. 5-4. This tube, when used as an amplifier, has a power output of 20 watts at an operating frequency of 400 megacycles per second. A somewhat similar but larger tube, utilized

for intermittent or pulse operation, is capable of generating up to 10 kilowatts of pulse-output power at a frequency of 1200 megacycles per second.

5–2. The Klystron

The close spacing of the electrodes and the utilization of cavity resonators extend the upper frequency limit in triode oscillators to about 1000 megacycles per second, but the power capacity is limited by the intense fields between the electrodes, and the interelectrode capacitances are too large for efficient resonant circuits. Moreover, high-frequency resistance of the conductors and dielectric losses cause inefficiency in these circuits. For sharp resonance, inductors and capacitors must have a high *figure of merit* or Q, which is defined as

$$Q = \frac{X}{R}, \qquad (5\text{–}1)$$

where X is the reactance in ohms, and R is the effective resistance in ohms of the inductor or capacitor. Values of Q range from about 20 to 100 for coils on iron cores used in broadly tuned low-frequency resonant circuits to approximately 30,000 for the sharply resonant silver-plated cavity resonators used in ultrahigh-frequency circuits.

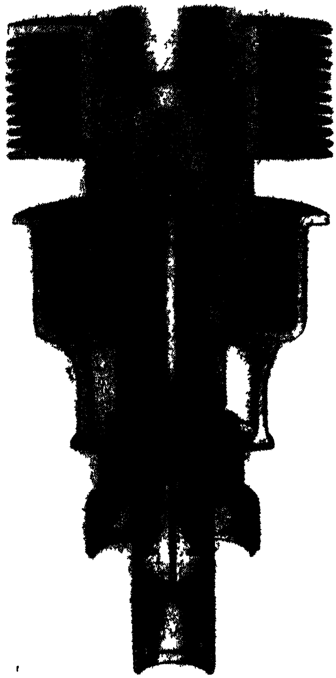


FIG. 5–4. Cutaway view of a miniature triode of the lighthouse type. Over-all length, 2.75 inches; diameter, 1.25 inches. *Courtesy Eitel McCullough, Inc.*

The frequency limitation imposed by the interelectrode capacitances of the tube may be seen by noting, for example, that in order to generate ultrahigh frequencies of 3000 megacycles per

second, with an inductor as low as 0.1 microhenry in the resonant circuit, the required capacitance would be only a fractional part of a micromicrofarad—a value impossible to achieve except with microscopic electrodes. Furthermore, the transit time required for electrons to pass from the cathode to the anode, even with high anode voltages, consumes the time equivalent to several cycles. These factors, therefore, definitely bar the use of triodes in ultrahigh-frequency amplifiers and oscillators.

The idea of producing a *velocity-modulated* electron beam was conceived by S. F. Varian in 1937, and shortly after this he with R. H. Varian and W. W. Hansen developed a vacuum tube, termed a *klystron*, that utilized this principle. In an ordinary triode, the electron stream varies in density according to grid potential changes; with velocity modulation the electrons are emitted from the cathode in the form of a beam of uniform density, accelerated to a constant velocity by a smoother grid, and then, in passing through another grid structure, they are accelerated if the potential is positive or decelerated if it is negative. If an alternating voltage is applied to the control grid, the electrons that pass through it during the time it is negatively charged move into the space beyond at a lower speed than those that pass through the grid at a later time when it is positively charged. The higher-speed electrons overtake the slower ones, and this results in concentrating or bunching the electrons in the field-free drift space beyond the grid. A suitable collector or catcher electrode is placed at an appropriate distance from the grid. The beam of electrons imparts its energy to the catcher in the form of periodic pulses, which correspond to the bunches, and the pulsations are then conveyed to an external circuit by suitable coupling means. Basically, therefore, velocity modulation consists of converting a uniform-density constant-velocity electron beam into one in which the electrons have a periodically higher and lower velocity, by virtue of which the electron beam is converted into one of variable density. This variable-density beam of electrons imparts energy to a resonant cavity if its natural frequency coincides with that of the arriving bunches of electrons.

The location of the parts of a klystron amplifier may be seen by referring to Fig. 5–5. All grids are designed with radial strips similar to the spokes of a wheel. The buncher consists of two grids that form the opposite walls of a re-entrant-type input

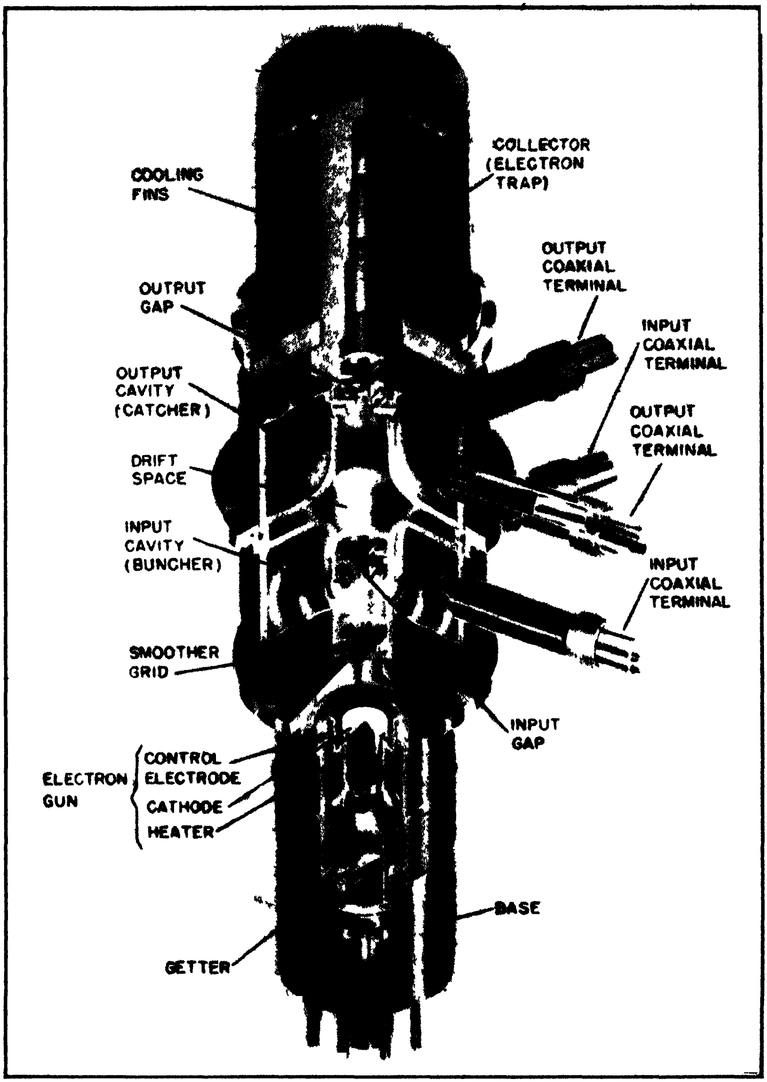


FIG. 5-5. Sectional view of a klystron. *Courtesy Sperry Gyroscope Company, Inc.*

cavity. The catcher or output cavity is similar to the input cavity, and both are equipped with small hairpin-shaped loops by means of which energy may be extracted from the output cavity through a coaxial terminal or inserted in the input cavity. Any energy that remains in the electron beam after it passes through the catcher is dissipated in the collector, which is equipped with fins for air cooling.

The bunching of electrons may be visualized graphically by means of the space-time Applegate diagram, Fig. 5-6, where for

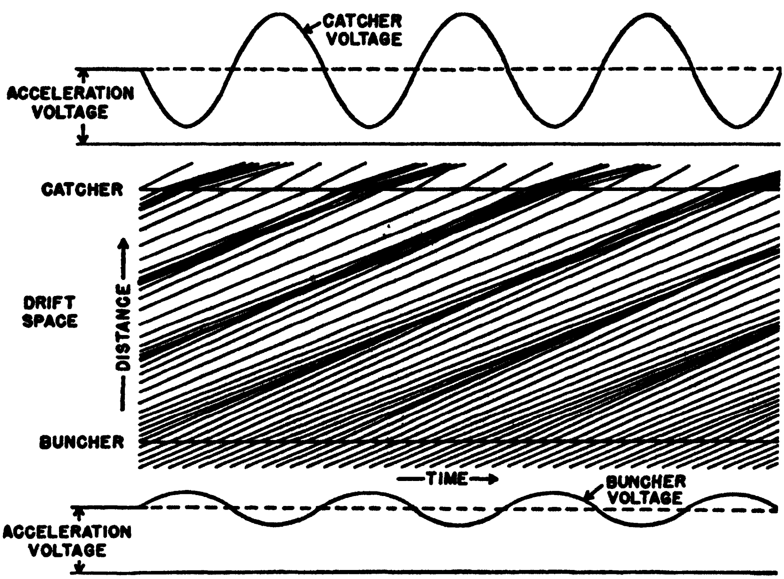


Fig. 5-6. Applegate diagram showing velocity modulation in a klystron.

any given electron the distance along the drift space is plotted as a function of time. The velocity of any electron at any instant, therefore, is represented by the slope of the line at that point; high electron velocities are indicated by steep lines. Equal slope lines at the bottom of the diagram show that the electrons enter the buncher as a beam of uniform density and velocity. Transit time across the buncher electrodes is assumed to be negligible, but the velocity of each electron as it crosses the gap is modified by the high-frequency field which varies according to the buncher voltage drawn below the diagram. The electron velocities increase, decrease, or remain constant, as indicated by

the slope of the lines in the drift space. The beam current at the catcher is nonuniform with respect to time and has a frequency component equivalent to the high-frequency buncher voltage. This voltage is shown at the top of the diagram. A simplified circuit of a klystron oscillator is shown in Fig. 5-7.

Adjustment of a klystron is very critical because tuning, which is accomplished by changing the capacitance between grids, also affects the spacing. The gain of a klystron amplifier varies between 5 and 20. As oscillators, the tubes are capable of delivering continuous power of about 50 watts at a frequency of 3000 megacycles per second. The more recently developed

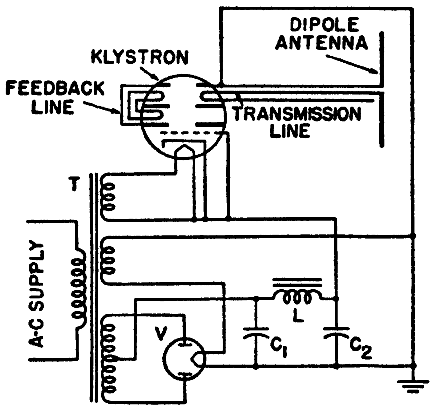


FIG. 5-7. Basic oscillator circuit for a klystron. The output circuit is connected to a dipole antenna.

single-cavity reflex klystron oscillators deliver about 1 watt at 10,000 megacycles per second and are capable of generating frequencies as high as 30,000 megacycles per second at an output power somewhat less than 0.1 watt.

High-frequency oscillators are frequently referred to as microwave generators, the frequency f in cycles per second and the wavelength λ in meters being related by the equation

$$\lambda = \frac{c}{f}, \tag{5-2}$$

where c is the velocity of electromagnetic radiation, that is, 3.00×10^8 meters per second. For the radiobroadcast band, covering from 550 to 1600 kilocycles per second, the corresponding

wavelengths range between 545.5 and 187.5 meters, whereas the radiation produced by a klystron operating at 30,000 megacycles per second has a wavelength of only 1 centimeter.

5-3. Magnetrons

Magnetic control of an electron stream in a vacuum tube, even though proposed as early as 1921 by A. W. Hull, found very little practical application until the principle was adopted in ultra-high-frequency oscillators. A simple *magnetron* is a diode in

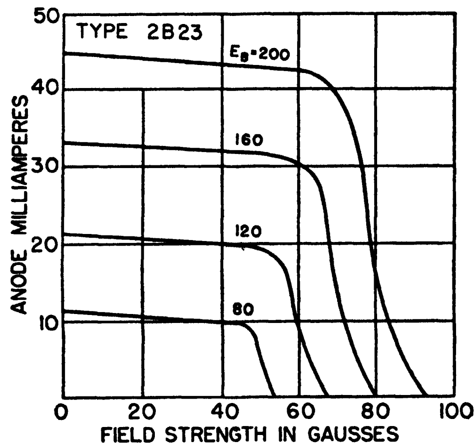


FIG. 5-8. Characteristic curves of a magnetron which has a cylindrical anode and an axially located cathode.

which the electrons are controlled by a magnetic field arranged so that it is perpendicular to the electric field that exists between the cathode and the anode. The electrons, emitted by a centrally located cathode, proceed in straight radial paths to the surrounding cylindrical, positively charged anode, but when an external magnetic field is applied the electrons are deflected in a curved path. As the field is increased the curvature of the paths of the electrons increases until they just miss the anode, with the result that the current to the anode drops abruptly to zero and the electrons return to the cathode after having gone through a heart-shaped path. Anode current in a simple magnetron is a function of the anode voltage and the strength of the magnetic field as shown in Fig. 5-8. The controlling magnetic field is con-

veniently obtained by inserting the magnetron in a solenoid through which an adjustable direct current flows. In an alternate arrangement a permanent magnet supplies a constant magnetic field, and anode-current cutoff is then obtained by lowering the anode voltage.

By combining the magnetron principle and a multicavity resonator in an electron tube, a magnetron oscillator capable of generating powerful ultrahigh frequencies suitable for radar

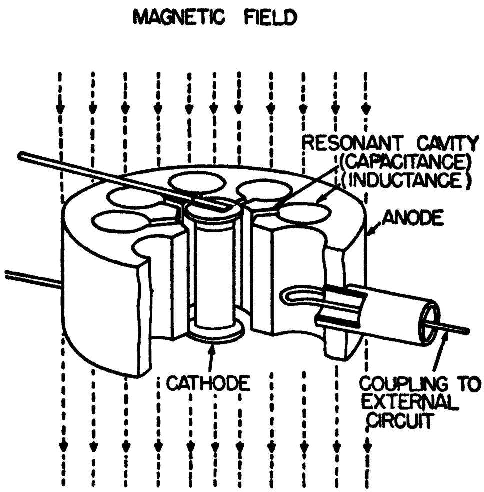


FIG. 5–9. Cutaway drawing of the electrodes in a multicavity magnetron. *Courtesy Bell Telephone Laboratories, Inc.*

transmission is obtained. The tube comprises a complete radio transmitter except for the power supply and the antenna. As indicated in the cutaway drawing, Fig. 5–9, the centrally located heater-type cathode is surrounded by a cylindrical anode which contains a number of symmetrically arranged resonant cavities. Vanelike metallic segments, extending between adjacent cavities, form the parallel surfaces for the capacity portions of the resonators. The magnetic field, indicated by the dotted line vectors, is supplied by a permanent magnet. A coupling loop for the extraction of high-frequency energy is mounted within one of the cavities.

During operation, a given electron emitted by the cathode is accelerated toward the positively charged anode and, as it moves,

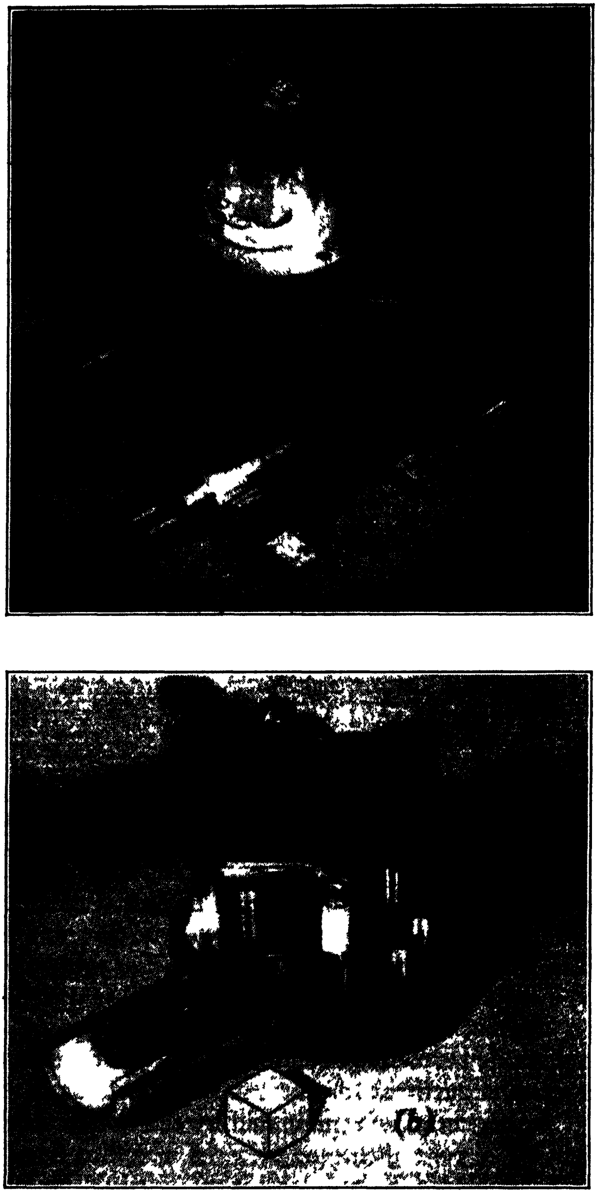


FIG. 5–10. (*a*) Three-centimeter magnetrons that use external magnets; (*b*) cutaway model of a 30-centimeter, high-power, tunable magnetron. One-inch cube is shown for size reference. *Courtesy Bell Telephone Laboratories, Inc.*

the stationary magnetic field causes it to traverse a curved path which is in a clockwise direction for the field indicated in the figure. An alternating electric field, due to the cavities performing as oscillating circuits and with opposite polarities on adjacent segments, also reacts on the flight of an electron. Its path is that of a cycloid, but with properly adjusted fields the electron comes to rest a short distance away from the cathode, after which the action is repeated until the electron reaches the anode. At each step, that is, at the end of every excursion where the electron has moved with the d-c field for a greater distance than it has moved against it, energy has been transferred from the stationary electric field to that of the oscillating field. Each step of an electron requires one-half period of the oscillating frequency, and in this time the electron moves from one cavity to the next. The oscillating field is directed so that it opposes that motion, and energy is delivered to the oscillating field until the electron ultimately arrives at the anode.

Magnetrons are built in a number of sizes and vary in diameter from about ½ to 10 inches or more. The smaller tubes, such as those shown in Fig. 5–10(*a*), generate 3-centimeter wavelengths and are used widely in airborne radar equipment; the larger tubes generate longer wavelengths. They have from 8 to 18 resonant cavities. When used as pulse transmitters, magnetrons operate at most for a few microseconds and deliver a peak output of 1000 kilowatts or more. They then remain inactive for the succeeding several hundred microseconds, and during this time they cool. The duration of the ultrahigh-frequency pulses is controlled by energizing periodically the anode with a direct voltage.

Multicavity magnetrons are essentially fixed-frequency devices and are not adaptable to tuning over a wide band of frequencies. Slight changes in frequency may be made in certain designs by adjustment through vacuum seals. A tube of this type is shown in Fig. 5–10(*b*). Transmission lines and hollow wave guides are commonly used to couple magnetron transmitters to radar antennas.

5–4. The Resnatron

A klystron can deliver about 100 watts and the magnetron can supply only a few kilowatts of ultrahigh-frequency energy continuously. In 1938 D. H. Sloan and L. C. Marshall developed

the *resnatron,* which is able to generate 50 or more kilowatts of ultrahigh-frequency energy continuously.

The tube, as shown in Fig. 5–11, is a tetrode and consists basically of a cylindrical cathode (composed of a large number of flat tungsten filaments), a control grid, an accelerating grid, an anode, and two resonant cavities. One of these cavities is located between the cathode and the control grid; the other, between the accelerator grid and the anode. The control and accelerator grids are arranged so that the flow of electrons from the cathode to the anode is not obscured; that is, radial beams of electrons leave the filaments of the cathode and have a clear path to the surrounding anode.

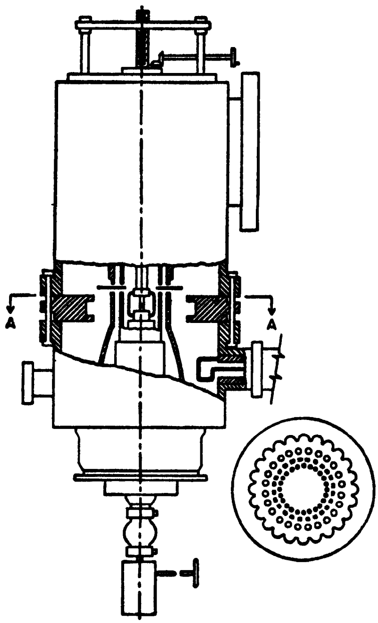


FIG. 5–11. Cutaway view of a resnatron. Insert shows cross section at A–A. *Courtesy Westinghouse Electric Corporation.*

The operation of the tube closely resembles that of the class C triode amplifier described in Sec. 3–7. The accelerator grid and the anode are at high positive potentials with respect to the cathode, but the control grid is biased negatively beyond the cutoff point. No electrons leave the cathode until the control-grid bias exceeds the critical value. As in a class C amplifier, this occurs only for a brief moment during any one cycle when electrons pass through the control grid at relatively low speeds and are accelerated to a high velocity by the positively charged accelerator grid. Their final velocity is governed by the acceleration they receive because of the high potential on that grid, and they arrive as a bunch. In the meantime the oscillating field has reversed the phase relations of the resonant cavity, of which the accelerator grid and anode are a part, and the electrons find themselves in a negative field where they slow down, impart their

acquired energy to the field, and reach the anode with negligible velocity.

The important problem of cooling is met in the resnatron by circulating water through the accelerator grid and the anode. The upper horizontal rod is the cathode-cavity tuning drive; the lower one adjusts the anode cavity. Coupling loops are used for feedback and for the removal of ultrahigh-frequency energy. A diffusion pump associated with the tube maintains the requisite vacuum.

A number of large resnatrons were constructed and gave excellent performance as radar countermeasures in World War II. Typical operating conditions require a filament power supply of 1800 amperes at 2 volts and an anode power supply of approximately 8 amperes at 17½ kilovolts. At these operating values, the tube delivers an output of about 85 kilowatts.

5–5. The Phasitron

In the cathode-ray tube, variation of the intensity and two-dimensional deflection of the electron beam is obtained; in effect this is equivalent to three-dimensional control. Either electric or magnetic fields provide the control means and make possible other special-purpose vacuum tubes. Several years ago, R. Adler proposed an ingenious tube termed the *phasitron*. It employs a focusing electric field to produce a horizontal circular disc of electrons; another electric field bends the disc in a vertical direction so that the edge follows a sinusoidal line and by its variation produces rotation of the profile about the vertical axis; and a third alternating magnetic field deflects the electrons in a circumferential direction and advances or retards the phase of the rotating corrugated electron disc with respect to a mean or normal angular velocity. This tube offers a simple means to phase-modulate a constant-amplitude carrier frequency in accordance with an audio frequency and greatly simplifies the circuit and construction of a frequency-modulated transmitter.

The tube is constructed with an axially located cathode, as shown in Fig. 5–12(*a*). An upper and a lower portion of the focusing electrode 1 acting in conjunction with another focusing electrode 2, both at a positive potential with respect to the cathode, cause the centrally emitted electrons to form into a tapered, thin-edged disc which we shall consider as a neutral

plane with the cathode as the axis. Electrons in the disc move radially toward two concentric anodes that have a still higher positive potential with respect to the cathode. The inner anode

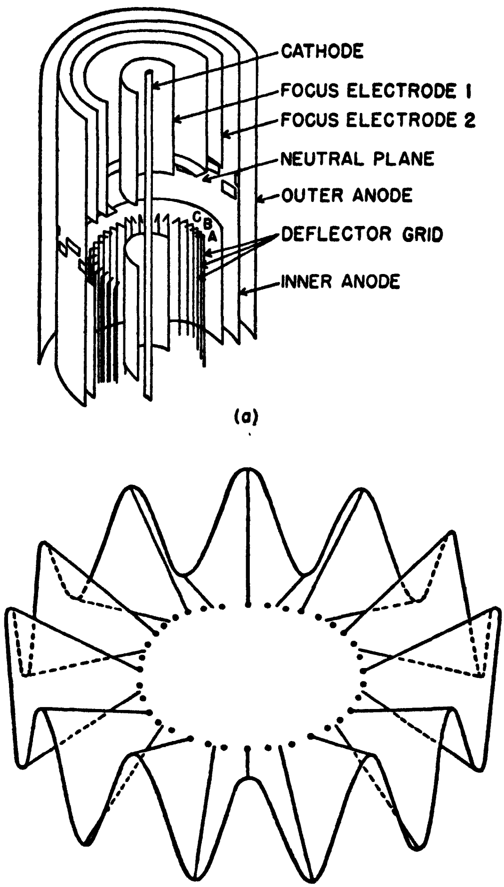


FIG. 5–12. (*a*) Diagram showing position of the electrodes in a phasitron; (*b*) appearance of the fluted electron disc if it were visible.

is made with a group of 24 evenly spaced rectangular holes, each alternate one being located above and below the neutral plane. No outer-anode current flows except when the electron disc is deflected so that electrons pass through the openings of the inner anode.

The deflector grid consists of 36 concentrically arranged wires with the top portion of each turned at right angles, like the spokes of a wheel, and located below the neutral plane. Grid wires are interconnected in three groups with every fourth wire connected to a particular group. When these wire groups are connected to a three-phase sinusoidally varying alternating voltage, the resulting field acts on the electrons in the disc, causes them to be sinusoidally displaced, and gives the disc a fluted configuration as shown in Fig. 5–12(*b*). The three-phase voltage on the deflector grid also produces a revolving electric field and synchronous rotation of the fluted electron disc. As the disc rotates, all electrons above the neutral plane pass through the upper holes, and those below that plane pass through the lower holes of the inner anode and proceed to the outer anode. At the instant when the *A* group of deflector-grid wires are at a maximum negative voltage, the 12 upper portions of the fluted electron disc pass through the corresponding upper holes in the inner anode, while the *B* and *C* groups, being positive at that instant, cause the remaining portions of the electron disc to pass through the 12 lower holes of the inner anode. The outer-anode current at that instant is, therefore, at its maximum, and the inner-anode current is at its minimum, value. At an instant one-half cycle later, the fluted portions of the electron disc are opposite the spaces between the holes of the inner anode, and the outer-anode current is then at its minimum and the inner-anode current is at its maximum value. Either anode current varies sinusoidally and at a frequency determined by the three-phase alternating voltage on the deflector grid.

The tube is mounted within a coaxial coil through which a varying audio-frequency current flows. The resulting magnetic field acts on the electrons comprising the fluted disc and displaces them counterclockwise or clockwise, that is, it increases or decreases the angular velocity of the electron disc in accordance with the direction and magnitude of the magnetic field. Rotational oscillations of the electron disc find a mechanical analogy in the hunting of an insufficiently damped rotor of a synchronous motor. The displacement of the disc produces a phase shift in the output current of the outer anode, and a phase-modulated carrier-frequency voltage is developed across the terminals of the load through which that current flows.

The simplicity of a frequency-modulated transmitter, incorporating the phasitron, may be inferred from the block diagram, Fig. 5–13. A modulation coil surrounding the tube is energized by the output of a push-pull audio-frequency amplifier. The coil is designed so that it contains very little resistance and consists of practically a pure inductance. Its reactance, therefore, for all practical purposes varies directly with the frequency,

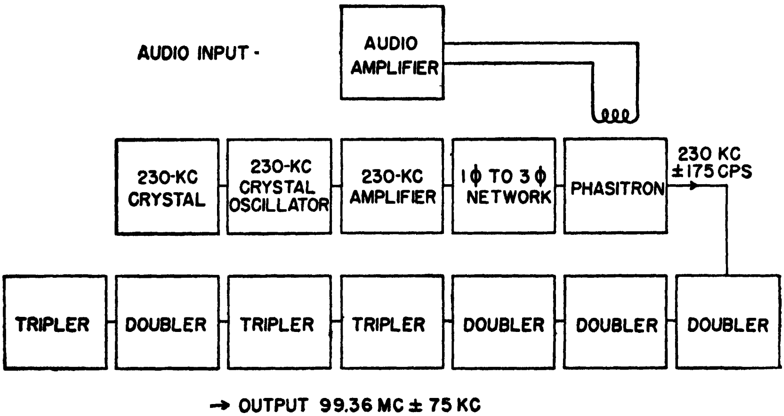


FIG. 5–13. Block diagram of a frequency-modulated transmitter utilizing the phasitron.

and the current through the coil decreases as the modulating audio frequency increases. The magnetic control field varies in conformity with the magnitude of the current and consequently phase-modulates the crystal-controlled oscillator frequency within the tube and effectively produces conversion of a varying amplitude-modulated signal into a corresponding frequency-modulated carrier. The two factors that change in an audio-frequency voltage are frequency and amplitude. Frequency finds its counterpart in a frequency-modulated carrier in the rapidity with which the carrier shifts in frequency about the crystal-controlled mean frequency; amplitude is reflected in the extent or deviation of the carrier frequency from its mean position. The block diagram shows a phase-splitting network that changes the carrier voltage from single phase to three phase. In a specific example, a 230-kilocycle-per-second voltage is impressed on a phasitron grid, and the changing magnetic field introduces a proportionate phase shift equivalent to plus or minus 175 cycles.

per second. The output of the phasitron passes through a group of frequency doubler and tripler stages, yielding a total frequency multiplication of 432. Such a transmitter delivers an average or a mean carrier of 99.36 megacycles per second, which

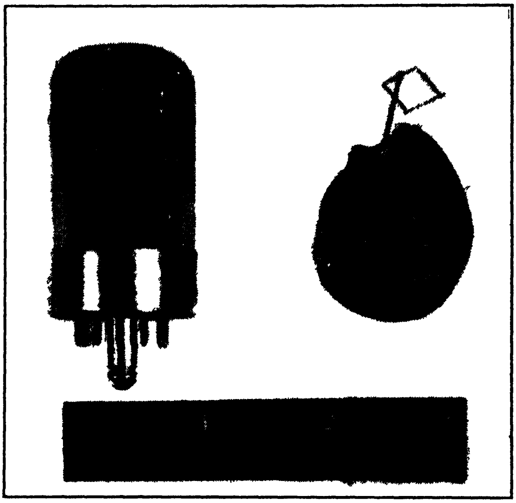


FIG. 5–14. Electronic transducer with movable anodes. *Courtesy National Bureau of Standards.*

remains constant because of the crystal-controlled oscillator but which is frequency-modulated to plus or minus 75 kilocycles per second.

5–6. Electronic Transducer Tubes

If the anode of a conventional triode is flexibly mounted, any mechanical acceleration causes a change in the relative position of that electrode with respect to the cathode and grid, and a corresponding change in anode current. This effect is utilized in an *electronic transducer tube,* where the movement of an anode translates a mechanical acceleration or displacement into a corresponding measurable voltage. A tube of this type, such as the one illustrated in Fig. 5–14, can be used to measure accelerations of high-speed aircraft, parachutes, and seat-ejection equipment used in jet-propelled airplanes. The tube contains a fixed, indirectly heated cathode, and two anodes in the form of plates are elastically mounted, one on each side of the cathode. When

these plates are deflected by an acceleration, the anode current changes proportionately.

Accelerations can cause movement only if they are directed normal to the plates, and consequently, depending on the number of axes to be explored, two or three tubes must be used to obtain a recording of other than linear accelerations. The elastic mounting of the plates has a fundamental frequency of about 800 cycles per second. The tube is commonly used in a Wheatstone bridge circuit, and a low-pass filter, which impedes the passage of any frequencies above 200 cycles, is inserted in the circuit to remove any natural frequency response. High output and wide frequency response make the recording of a rapidly varying acceleration possible; no auxiliary amplifier is required. Accelerations of the order of 10 times gravity may be measured directly on a standard oscilloscope.

In another electronic transducer, the vacuum-tube electrodes of a triode are inclosed in a small metallic tube approximately 1 inch long and about ¼ inch in diameter. The cathode and grid leads are brought out through a glass seal at the base of the tube. The anode is attached to a very thin flexible metal diaphragm at the top of the tube, and the anode circuit is completed through the metal housing. A small arm projecting from the diaphragm on the outside of the tube, when moved, converts a mechanical displacement or movement into a corresponding variable anode current.

5-7. X-ray Tubes

While studying the performance of an electric current in a simple vacuum tube, W. K. Röntgen in 1895 noticed that a cardboard coated with barium platinocyanide salts fluoresced even though it was located some distance from the tube. Subsequent experimentation disclosed that the rays, which he termed *X rays*, are produced when rapidly moving electrons are suddenly stopped on striking a target; that they are propagated in straight lines; and that they, like light, may be reflected, refracted, diffracted, and polarized. In fact, they are a part of the electromagnetic spectrum and cover the range of wavelengths between about 0.25 and 1000 angstrom units.

Early X-ray tubes consisted of two or sometimes three electrodes mounted in a partially evacuated glass envelope. During

operation the electric field between the cold cathode and the anode ionized the residual gas, and the resulting positive ions bombarded and released electrons from the cathode. These, in turn, bombarded the anode, or anticathode, as it was termed, and caused X rays to be generated. The intensity of the rays was varied by changing the voltage between the anode and cathode and by regulating the residual gas pressure.

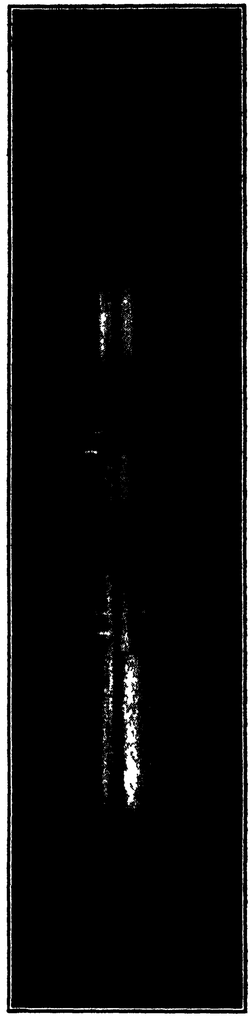


Fig. 5-15. A 400-kilovolt Coolidge X-ray tube designed for operation in oil. *Courtesy General Electric X-Ray Corporation.*

Development by W. D. Coolidge in 1912 of the hot-cathode high-vacuum X-ray tube introduced stability and uniformity of performance and also gave complete control of the intensity and penetrating power of the rays. The cathode of the Coolidge tube is made in the form of a coiled tungsten filament, and the anode usually consists of a tungsten target. The anode surface is placed at an angle with respect to the axis of the tube, and the X-ray beam, originating from the focal spot on the anode, passes through the wall of the tube. Only about 1 per cent of the kinetic energy acquired by the electron stream is converted into X rays; the remainder is converted into heat, and provisions must be made, particularly in the large sizes, to cool the anode. In some designs the target is imbedded in a copper mounting arranged so that water may be circulated within the mounting; in other types the anode extension beyond the seal is equipped with radiating fins for natural or forced air cooling; still others allow the tube to be operated while immersed in oil. A Coolidge X-ray tube, suitable for operation in oil, is illustrated in Fig. 5-15. The anode voltage, which

ordinarily ranges between 30 and 400 peak kilovolts, is obtained from a half- or preferably from a full-wave rectifier. Current through an X-ray tube varies between 2 and 1000 milliamperes and is adjusted by changing the filament current which changes the cathode temperature.

X rays are absorbed differentially in their passage through matter, and the results are determined by noting the densities of the shadows on a fluorescent screen or on a photographically exposed X-ray film. Films used for this purpose consist of a very thin layer of gelatin containing an emulsion extremely sensitive to light and coated on both sides of a transparent base material. Since less than 1 per cent of the incident X-ray energy is absorbed by the film to form the latent image, calcium tungstate-coated intensifying screens are placed adjacent to the film on each side. During exposure the calcium tungstate salt fluoresces in proportion to the intensity of the X rays; it emits ordinary light that intensifies the exposure and reduces the exposure time to as much as $\frac{1}{40}$ of the time required without intensifying screens. Tubes with small focal spots produce better definition in radiographs than large ones but are limited in their current-carrying capacity and cannot be used for long exposures without causing serious anode erosion. The anode of a standard diagnostic X-ray tube must withstand loadings of the order of 200 milliamperes at 80 kilovolts distributed over a focal spot area of about 0.155 square centimeter. The generated heat, equivalent to 103 kilowatts per square centimeter, causes the focal spot to reach temperatures almost equal to the melting point of tungsten.

X-ray equipment is used extensively in medical diagnosis and therapy. In industry, radiographs are taken of steel castings, which require a great deal of costly machine work, or of parts which on failure may cause serious damage and possible plant shutdown. A radiograph of a defective casting is shown in Fig. 5–16. X rays are used to inspect machine parts or castings for cracks, slag or oxide inclusions, shrinkage areas, and the like. They are a valuable engineering aid in checking casting design. Fluoroscopes activated by X rays are used industrially in the examination of automobile tires, packaged foods, and citrus fruits; as an inspection tool in foundries; and for checking inserts for proper location in molded plastics.

Powerful X-ray equipment, in which the tube and auxiliary equipment are designed for operation as high as 2,000,000 volts, has been developed within recent years. The tubes are of the

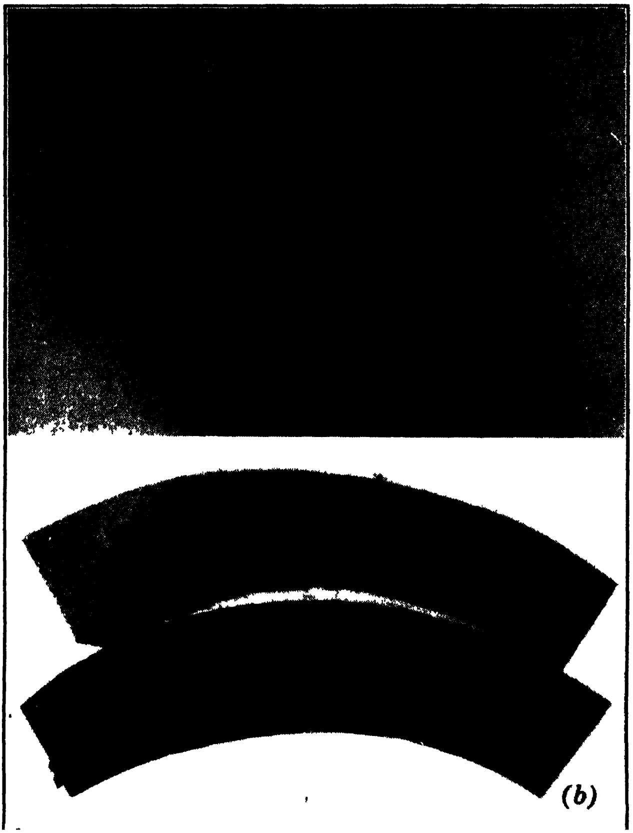


FIG. 5–16. (a) Radiograph of a casting for a high-pressure steam line in a power plant; the crack at the chaplet indicates a faulty casting technique. (b) Photograph of the casting after sectioning through the crack. *Courtesy General Electric X-Ray Corporation.*

multisection type and consist of a number of glass cylinders fused to metal rings equipped with internal electrodes to focus the electron beam which originates from the cathode located at one end. A sectional drawing of a 2,000,000 volt mobile X-ray unit, rated to operate continuously at a current of 1.5 milliamperes, is shown in Fig. 5–17. The resonance power-supply

transformer, which is designed to operate at a frequency of 180 cycles and which does not require an iron core, is arranged with the X-ray tube mounted in the central space. This construction facilitates making electrical connections to the 23 intermediate stainless-steel electrodes and also provides electrostatic

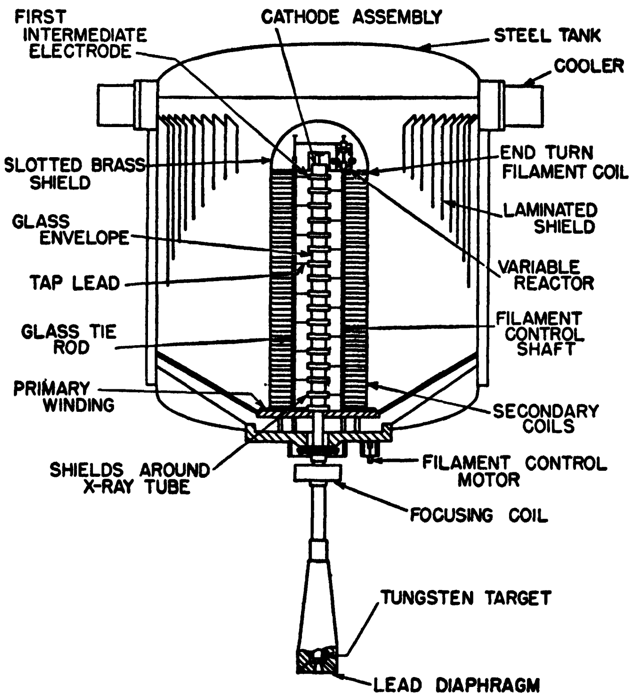


FIG. 5–17. Cutaway drawing of a 2,000,000-volt mobile X-ray unit. *Courtesy General Electric X-Ray Corporation.*

shielding for the tube. Narrow silicon steel strips are welded to the interior of the tank which houses the unit; they offer a low-reluctance path for the magnetic flux of the transformer. Freon gas at a pressure of about 55 pounds per square inch within the tank supplies the necessary insulation and cooling. The copper-backed tungsten target is located in an extension chamber; both are water cooled.

The lower terminal of the coil and the anode are grounded as shown in the simplified circuit, Fig. 5–18. A three-phase motor *M* drives the separately excited 180-cycle alternator *G*, which is

connected to the primary winding P of the resonance transformer. Capacitance to ground of the slotted brass shield at the top of the transformer together with other capacitances and the inductance of the secondary winding are chosen so as to make the natural frequency of the transformer 180 cycles per second. In the diagram this is represented equivalently by the addition of the capacitor C_1 in the primary circuit. The secondary winding has taps for connection to the intermediate electrodes. The filament current is adjusted by means of a

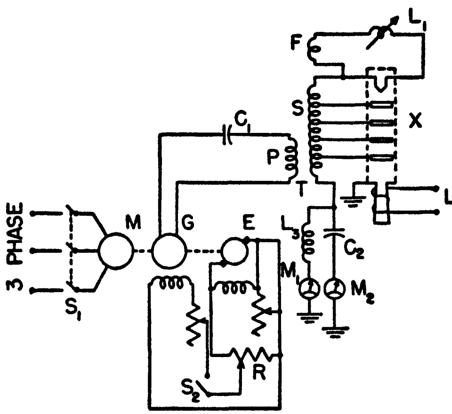


FIG. 5–18. Simplified circuit of the 2,000,000-volt mobile X-ray unit and associated equipment.

variable reactor L_1, and the diameter of the electron beam, which determines the size of the focal spot, is controlled by varying the magnitude of a direct current through the focus coil L_2. A d-c milliammeter M_1 registers the electron current through the tube; the a-c milliammeter M_2, calibrated in megavolts peak, indicates the secondary charging current that passes through the capacitor C_2.

The unit is of the self-rectifying type; that is, electrons emitted by the cathode are accelerated toward the anode only when the anode has a positive potential with respect to the cathode. An industrial high-voltage X-ray installation is illustrated in Fig. 5–19. The penetrating power of the generated X rays is so intense that with a target-to-film distance of 3 feet the exposure time for a 1,000,000-volt unit, operating at 3.0 milliamperes through 4 inches of steel, is only about 1.5 minutes.

The 2,000,000-volt unit produces an even more intense beam and requires still less exposure time; for the same conditions and with an operating current of 1.5 milliamperes the exposure time is only 6 seconds.

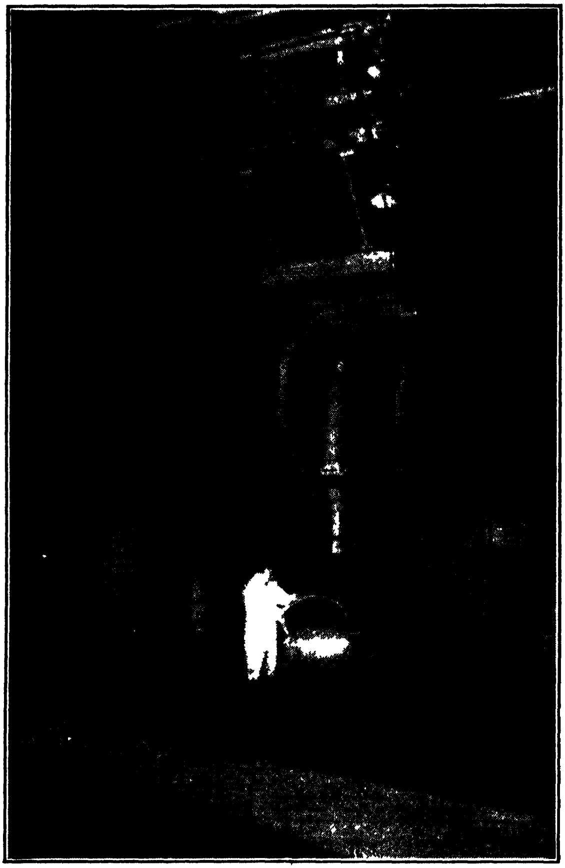


FIG. 5–19. An industrial installation of a 1,000,000-volt X-ray unit used for inspection of large castings and welds. *Courtesy General Electric X-Ray Corporation.*

An analysis of X radiation discloses that a range of wavelengths exists, that the longest wavelength depends on the transparency of the tube window, and that the shortest wavelength depends solely on the magnitude of the anode-to-cathode voltage. Kinetic energy acquired by electrons, which are accelerated in a

vacuum within a diode, was given by the equation $Ve = \frac{1}{2}mv^2$ (Eq. 1–9). In the case of electrons that are accelerated within an X-ray tube, their energy of Ve electron volts is transformed, when they are suddenly stopped at the target, into electromagnetic radiation according to the equation

$$Ve = \frac{1}{2}mv^2 = \frac{hc}{\lambda_0}, \qquad (5\text{–}3)$$

where V is the maximum voltage applied between anode and cathode, e is the electron charge (1.60×10^{-19} coulomb), m is the electron mass (9.11×10^{-31} kilogram), v is the electron velocity in meters per second, h is Planck's constant (6.62×10^{-34} joule second), c is the velocity of light (3.00×10^8 meters per second), and λ_0 is the minimum wavelength in meters of the specific group or band of X rays. From this equation the minimum wavelength in angstrom units and the maximum voltage across the tube are related by the expression

$$\lambda_0 = \frac{12{,}350}{V}. \qquad (5\text{–}4)$$

The continuous radiation intensity of X rays varies directly with the current through the tube and approximately as the square of the voltage across it. Furthermore, it varies with the atomic number of the target material; the higher the atomic number, the more intense the beam. When the anode voltage for a given target material is increased to a sufficiently high value, for instance up to 80 to 100 kilovolts for tungsten, characteristic rays appear superimposed on the continuous spectrum. These rays consist of a number of clearly defined wavelengths, some more intense than others. They occur in groups, and the major ones are designated as the *K*, *L*, and *M* groups. Tungsten, for instance, emits groups of characteristic rays which have wavelengths of the order of 0.2, 1.4, and 6.9 angstrom units. They are produced when target material electrons are dislodged from atomic shells that have the same letter designation. The fact that electrons move from outer to inner orbits and in doing so emit radiant energy accounts for the various X-ray groups and the individual characteristic rays within them. The greatest energy changes, that is, those which occur near the nucleus and are designated as the *K* group of wavelengths, are the shortest

and the most intense. By interposing a suitable absorbing metal filter between the X-ray source and the point of application, the continuous X-ray spectrum may be eliminated and only the characteristic rays remain; even some of these may be absorbed to the extent that only the most intense rays remain to yield a beam of monochromatic X rays.

5-8. X-ray Diffraction

Much of the mystery surrounding the nature of X rays was clarified in 1912 when von Laue and his assistants diffracted the rays by means of the natural grating of crystalline plates. Al-

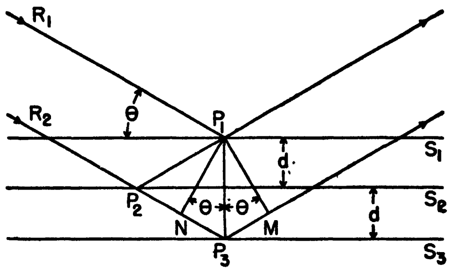


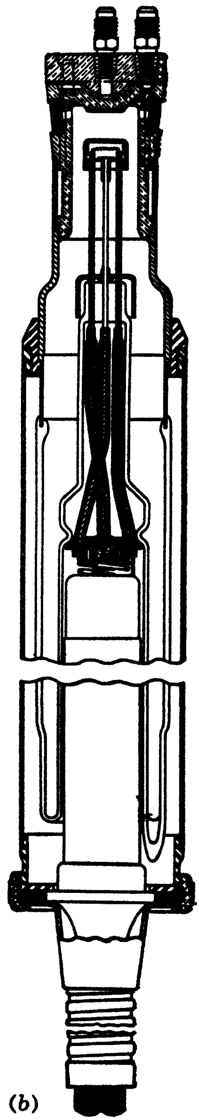
FIG. 5-20. Reflection of monochromatic X rays from the parallel planes of a crystal.

though this demonstrated that X rays are electromagnetic radiations similar to visible light, the later-developed quantum theory regarded X rays, and light as well, as quanta of energy or *photons*. Both concepts have contributed greatly to the development of modern physics. Von Laue's analysis was simplified materially by W. H. and W. L. Bragg, who considered X rays to be reflected by the parallel planes of a crystal and who showed by experiments that diffraction may be considered to be the simple reflection of an incident, monochromatic X-ray beam. In Fig. 5-20 the successive parallel planes of a crystal, separated by a distance d, are designated as S_1, S_2, and S_3. Two parallel rays R_1 and R_2 of the X-ray beam impinge on the crystal at an angle θ. The line P_1N is drawn perpendicular to R_1, and from the drawing it is evident that the ray R_2 must travel the additional distance NP_3 or $2d \sin \theta$ before it strikes the reflecting surface S_3. If either distance NP_3 or NP_3 plus P_3M is equal to a wavelength λ or an integer number of wave-



(*a*)

FIG. 5-21. (*a*) X-ray diffraction tube of the shockproof type; (*b*) cutaway drawing of the tube. Water-cooled anode is at the top. *Courtesy Machlett Laboratories, Inc.*



(*b*)

lengths, the reflected waves from the successive crystal faces are in phase. Reflection, therefore, takes place only at the incidence angle given by the expression $n\lambda = 2d \sin \theta$. See also Eq. 4-16.

When the wavelength, the order of the spectrum, and the incident angle θ are known, X-ray diffraction can be used to determine the distance between molecular or atomic planes, and consequently analysis can be made of any material by measuring and comparing the pattern recorded on a photographic film. For instance, some antifouling marine paints are made with certain percentages of cupric and cuprous oxides. Since each of these oxides yields its own diffraction pattern and the relative densities of the lines in the composite pattern indicate the relative amounts of each oxide, an analysis is easily made.

The Pyrex glass of ordinary X-ray tubes absorbs the rays quite readily and practically prevents any transmission through a window 0.040 inch thick if the rays are longer than 1.5 angstrom units. Beryllium is much more transparent. A typical water-cooled X-ray diffraction tube, having a target arranged at a 6° angle and equipped with two beryllium windows, is illustrated in Fig. 5-21.

Diffraction equipment for industrial use is commonly designed in the form of a self-contained unit and arranged so that the X-ray tube is mounted vertically in a central position at the top, as shown in Fig. 5–22. Diffraction cameras of various types



FIG. 5–22. X-ray diffraction equipment. *Courtesy Harshaw Chemical Company.*

may be mounted on accurately adjustable ways. Three major methods of analysis are illustrated in Fig. 5–23. In ordinary diffraction with a Laue camera, the X-ray beam passes through the specimen and, if the specimen is a single crystal, produces a diagram of spots symmetrically disposed about the center. Fine powders of chemical substances or crystalline aggregates may be substituted for a single crystal, in which event the reflect-

ing surfaces of a sufficiently great number of particles in the random displacement are turned so that reflection occurs and the pattern on the photographic plate consists of a series of concentric rings similar to the electron diffraction pattern shown previously in Fig. 4–24(*b*). Each of these rings has a uniform

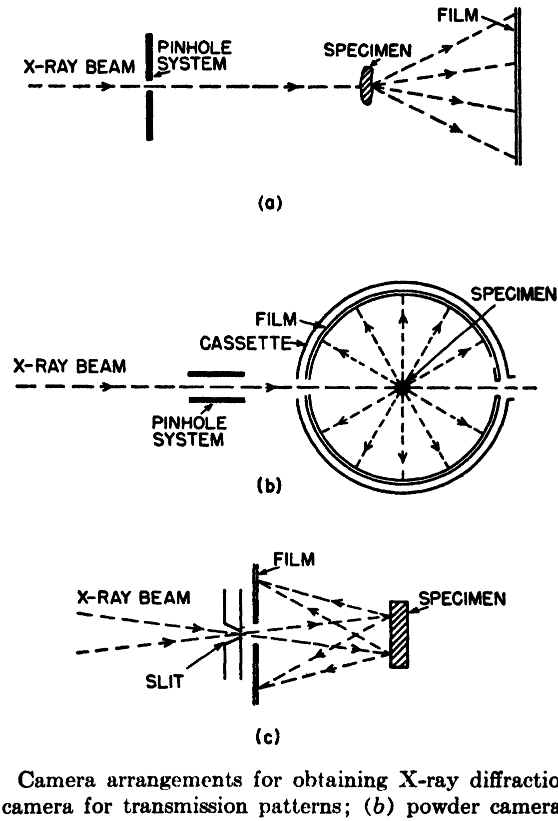
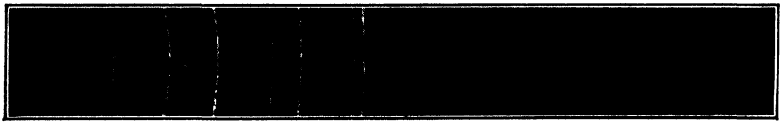


FIG. 5–23. Camera arrangements for obtaining X-ray diffraction patterns. (*a*) Laue camera for transmission patterns; (*b*) powder camera; (*c*) back reflection camera.

intensity and corresponds to one set of reflecting planes. A section taken through a diameter of a diagram yields a line spectrum. Such a pattern is conveniently obtained on a camera where the strip of film is arranged around 360° with the specimen located at the center, as shown in Fig. 5–23(*b*). A small hole in the film allows the X-ray beam to pass and acts as an index point. Diffraction spectra of the powder type, such as those given in

Fig. 5–24, are employed for routine identification of unknown substances.

The back reflection camera, Fig. 5–23(*c*), is used for the precise measurements of lattice constants, measurement of surface stresses, observation of distortion in crystals, and the determination of composition of solid-solution alloys.



(*a*)



(*b*)



(*c*)

FIG. 5–24. Typical X-ray diffraction patterns taken with a powder camera. (*a*) Artificial ruby; (*b*) boehmite; (*c*) nickel foil. *Courtesy Harshaw Chemical Company.*

X-ray diffraction patterns give us the distances between interplanar spacings of molecules and atoms. These data should permit us to accurately produce a photographic representation of the structure, and, in fact, such a procedure was originally proposed by W. L. Bragg. The diffraction spots are assigned indices denoting the orientations of the reflecting planes of the atom relative to the unit cell. Intensities are measured and corrections applied to arrive at certain structure factors which, however, are independent of the crystal structure. In the second step, successive exposures are made on a single film through a number of special masks consisting of films on which there are previously prepared patterns of various widths, spacings, and orientations. The masks used are determined by the indices of the X-ray diffraction spots and the structure factors which also control the

relative lengths of exposure. The photograph obtained after the multiple exposure shows the structure of the molecule or atom. A molecule of hexamethylbenzene magnified about 50,000,000 times is shown in Fig. 5–25. The carbon atoms are indicated clearly, but the hydrogen atoms, of which there are 3 to each

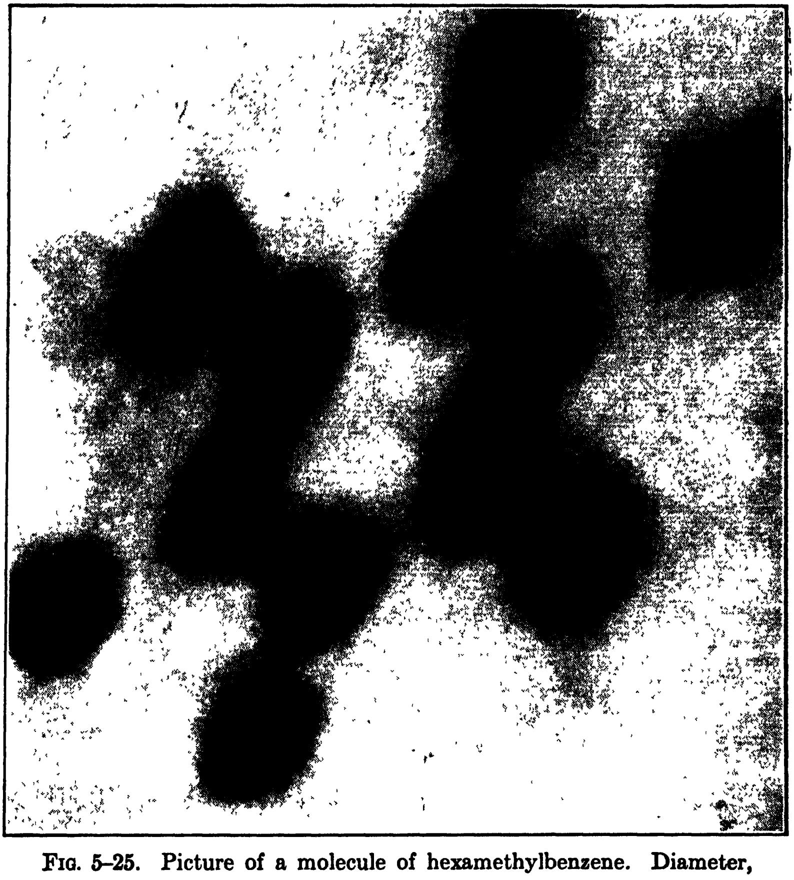


FIG. 5–25. Picture of a molecule of hexamethylbenzene. Diameter, $\frac{1}{40,000,000}$ inch. *Courtesy Eastman Kodak Company.*

of the 6 carbon atoms of the outer ring, do not show because their diffracting power for X rays is negligible. The arrangement of the atoms in this molecule is precisely that previously deduced by organic chemists. Although the finished picture is not a simple print through a negative, the mathematical steps

involved in obtaining from the X-ray diffraction pattern the information about the band patterns to use, and the exposure times through each, satisfy rigorously the laws of physics. The final result can, therefore, be said to represent a true picture of the actual molecular structure.

5-9. Field-emission X-ray Tube

A tungsten-filament emitter is entirely inadequate to supply the electron current to produce the high-intensity X-ray beam

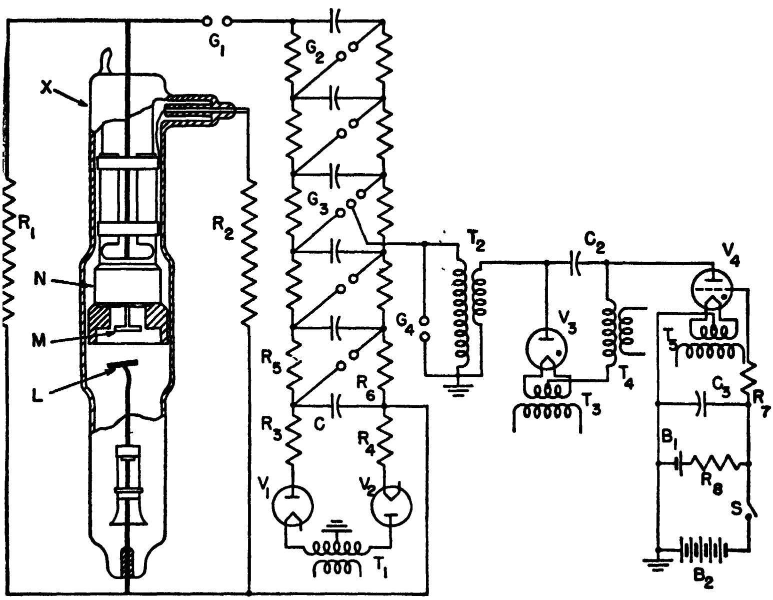


FIG. 5-26. Schematic diagram of a high-speed X-ray tube and associated equipment. *Courtesy Westinghouse Electric Corporation.*

required for exposures of only a few microseconds. This limitation has been removed by the development of a *field-emission X-ray tube,* which consists of a cold-cathode emitter, a discharge-initiating electrode, and a tungsten anode, acting as the target, mounted in an evacuated envelope.

The cathode is a small rectangular piece of molybdenum arranged within a slot of a trough-shaped auxiliary electrode which also acts as a focusing cup. As may be seen from the schematic circuit diagram, Fig. 5-26, this electrode N is connected to the

anode L through a high resistance R_2. During operation, the sharp edges on the anode, located close to the cathode M, concentrate the electric field, and a discharge is initiated which is then forced by the voltage drop across the high resistance to transfer to the anode.

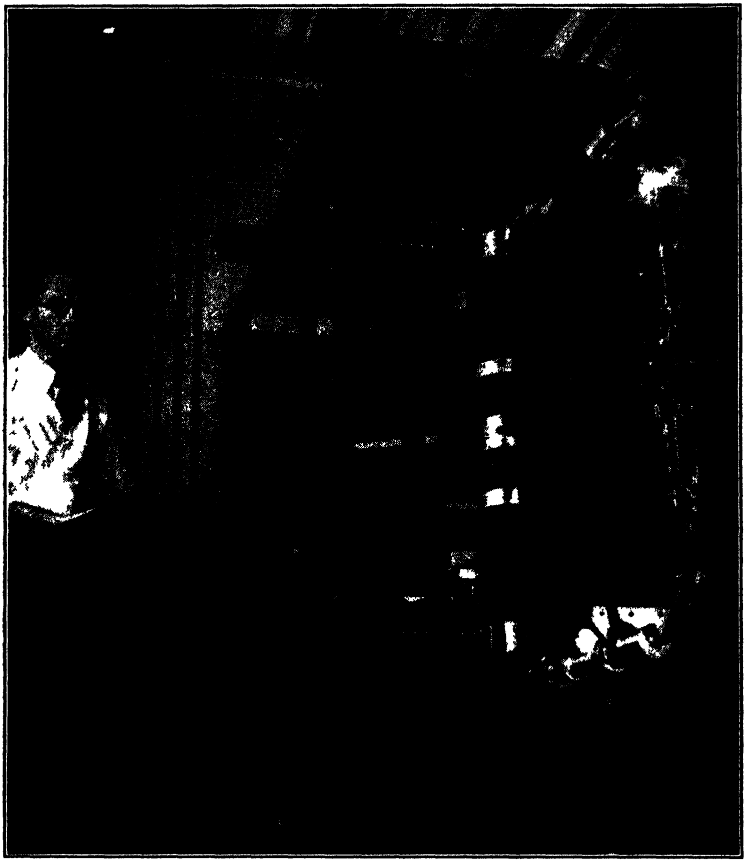


FIG. 5–27. Marx circuit surge generator equipment and high-speed X-ray tube. *Courtesy Westinghouse Electric Corporation.*

A very large but brief burst of power of approximately 600,000 kilowatts is supplied by a Marx-circuit surge generator shown to the right of the tube. The rectifier tubes V_1 and V_2 charge each of six capacitors C to a potential of 50 kilovolts through a group of resistors. The individual spark gaps G_2 and the special

gap G_3 are adjusted just below the point of voltage breakdown. Capacitor C_2 in the trigger circuit is charged to about 1000 volts. When the switch S is closed the charge on the grid of

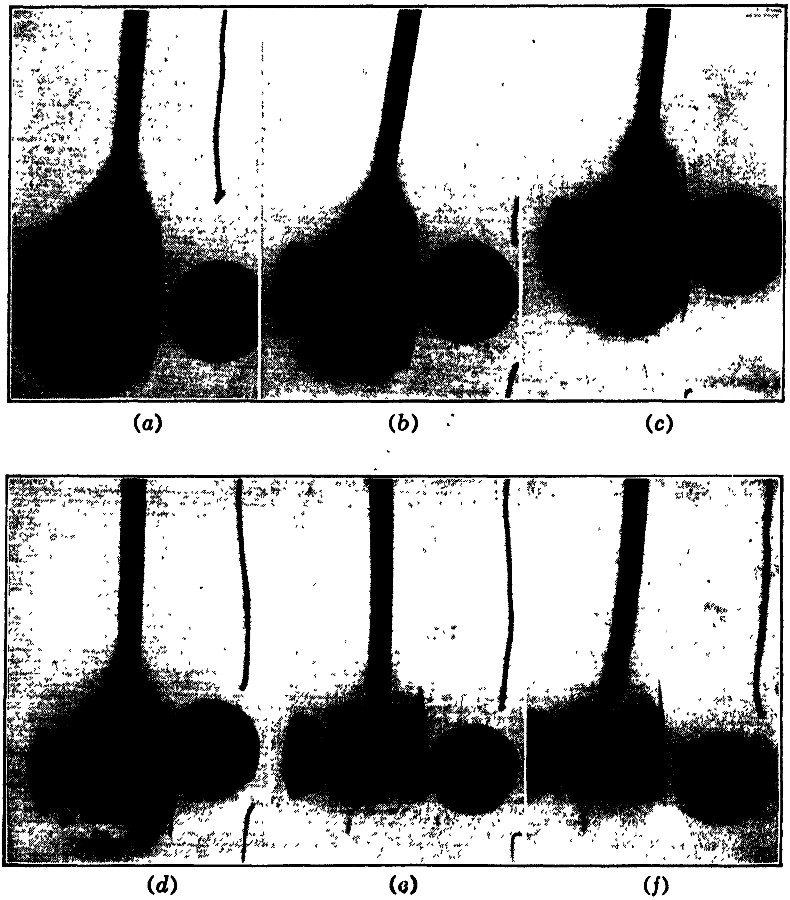


FIG. 5-28. Series of high-speed radiographs showing deformations of a golf ball and club during impact. Ends of wires which caused exposures by being open-circuited are shown at the right. *Courtesy Westinghouse Electric Corporation.*

V_4 in the timer circuit is dissipated, and C_2 then discharges through the primary winding of the induction coil T_2. The secondary winding delivers a high-voltage impulse to initiate a flashover at the spark gap G_3, causing all the gaps of the surge

generator to break down, and the total output potential of all the capacitors C in series, that is, 300 kilovolts, is impressed on the tube electrodes M and N. The high field causes electrons to be emitted from the cathode, and the discharge of the capacitors develops into an arc between the cathode and the focusing anode and then immediately thereafter to the anode, with the consequent production of high-intensity X rays. The high stabilizing resistance R_1 is connected across the cathode and the anode to facilitate consistent firing. A surge generator with X-ray tube is illustrated in Fig. 5–27.

The timing circuit may be adjusted to produce a time interval ranging from 20 to several thousand microseconds. With slight changes, the circuit may be arranged to cause operation when the switch S is opened instead of closed, and exposures of this kind are made when the object under observation is used to break a conducting lead. The series of radiographs of a golf ball starting its flight, shown in Fig. 5–28, was made with such a timer connection. X-ray equipment of this type is applied extensively to the field of ballistics and is helpful in the solution of many mechanical problems, such as the determination of strains in the blades of steam and gas turbines and the analysis of valve action in reciprocating engines.

5–10. Artificial Radioactivity

Other large special-purpose vacuum tubes, installed mainly in research laboratories, contribute to the extension of our knowledge of atomic structure and make available other important research tools. These devices resemble electric generators in size and with their auxiliary apparatus look like power plants. Their development dates from about the time of the discovery of X rays, when A. H. Becquerel noted that invisible radiation, termed *radioactivity*, was emitted spontaneously by various uranium compounds. Later P. and M. S. Curie verified this action on a number of the heavy elements and discovered the radioactive elements polonium and radium.

Subsequent analysis disclosed that this radiation consists of three components, designated as *alpha*, *beta*, and *gamma* rays; these were later identified as positive ions or nuclei of helium, high-speed electrons, and extremely short electromagnetic waves, respectively. In the process of emitting these rays, the radio-

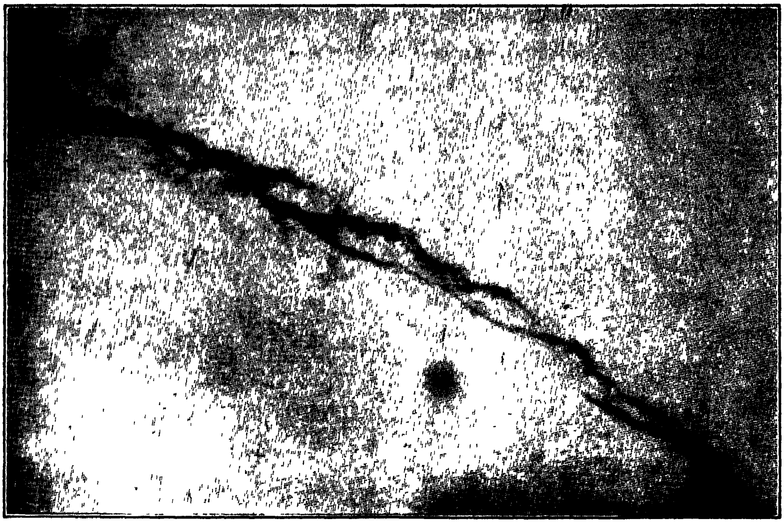
active substance gradually disintegrates into an element of lower atomic weight and number. Radium of atomic number 88, for instance, passes through at least ten distinct forms before it reaches stability as lead with an atomic number 82. Some transmutations are accompanied by the emission of alpha particles, and others by the simultaneous emission of beta particles and gamma rays. The time required to convert one-half the substance, termed its half-life, varies from 1690 years for the change of radium to radon to only 3 minutes for the change of radium A to radium B. The rate of disintegration is proportional to the remaining number of original particles of the radioactive substance, and the disintegration time varies logarithmically as given by the equation

$$M = M_0 \epsilon^{-\delta t}, \tag{5-5}$$

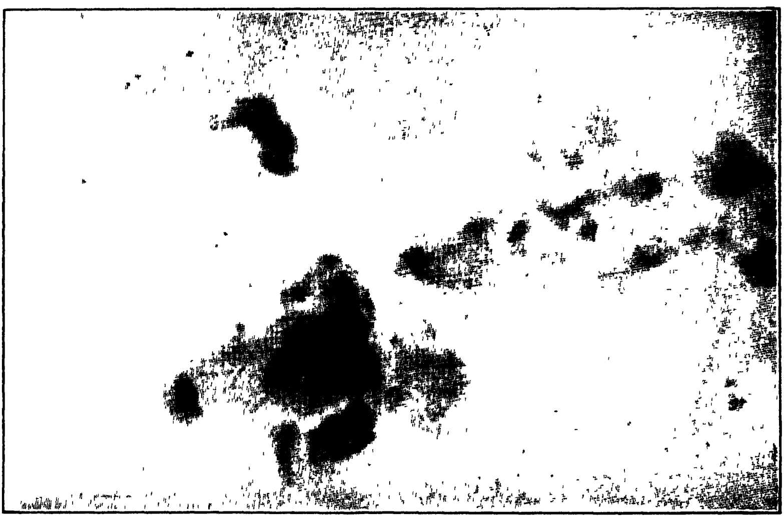
where M_0 is the initial mass, M is the mass at a subsequent time t, ϵ is the Napierian base, and δ is the decay constant of the substance.

Alpha particles are ejected with very high velocities and are able to ionize air and pass through thin metal foil or sheet. Beta particles reach even greater velocities; in fact, some of these nearly reach the speed of light, but because they are so much lighter than the alpha particles they are more easily deflected during collisions with air atoms. Gamma rays are extremely penetrating radiations and have wavelengths which range from about 0.005 to 1 angstrom unit. They are utilized in medical therapy and in industrial radiography. Two typical gamma radiographs taken through thick steel castings are illustrated in Fig. 5–29.

Artificial transmutation of an element was achieved by E. Rutherford in 1919 by bombarding nitrogen with alpha particles and causing protons or hydrogen nuclei to be driven from the nuclei of nitrogen. This astounding discovery received an additional impetus in 1934 when I. and F. Curie Joliot announced the production of an *artificial* radioactive substance obtained by bombarding aluminum with high-speed alpha particles. The relative scarcity and high cost of radium coupled with the paucity of alpha particles for large-scale experiments caused the development of electrical apparatus to accelerate large numbers of helium ions or, preferably, deuterons. Deuterons are the



(a)



(b)

FIG. 5-29. Typical radiographs obtained by means of gamma rays. (a) An aggregate of cracks in cast steel; (b) slag inclusions in a steel casting. *Courtesy Canadian Radium & Uranium Corporation.*

nuclei of deuterium, that is, the $_1H^2$ isotope of hydrogen, which has an atomic weight of 2. The necessary acceleration is obtained by impressing a large difference of potential between the two electrodes of a vacuum tube, liberating the positively



FIG. 5–30. Electrostatic generator mounted on top of a two-story laboratory. *Courtesy Westinghouse Electric Corporation.*

charged or ionized particles at the anode, and having them proceed to the cathode where they act on a suitable target material.

Many problems are involved in the construction of a linear accelerator; the required voltage may range up to several megavolts, and the associated insulation problems are complex. An interesting research laboratory installation is illustrated in Fig. 5–30; it is shown partially sectionalized in Fig. 5–31. The 47-foot high pear-shaped pressure vessel mounted on the building contains a high-voltage generator and a special vacuum tube. A Van de Graaff electrostatic generator, consisting of an endless fabric belt that acquires a positive charge at the low portion of its travel from a vacuum-tube rectifier, carries the charge to the top, and delivers it to the high-potential terminal, supplies the requisite accelerating voltage. The apparatus, en-

closed in the tank with gas under pressure, permits voltages up to 5,000,000 volts to be obtained without flashover, and this potential difference can be applied to the terminals of the 40-foot

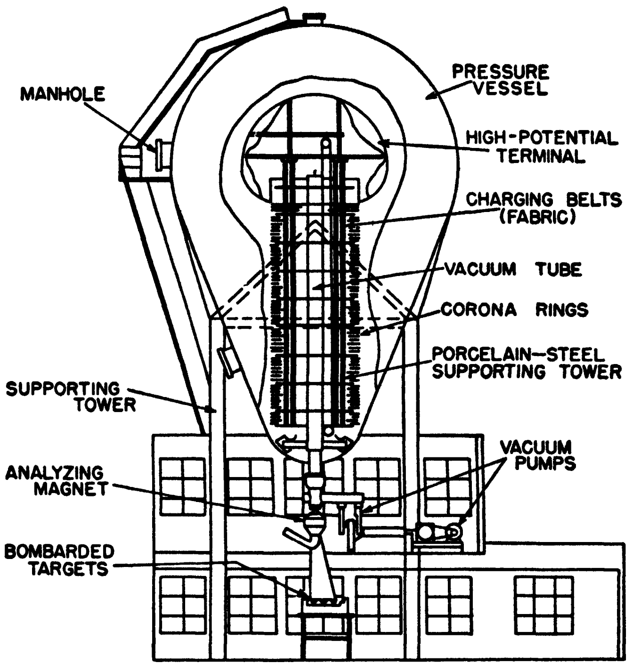


FIG. 5-31. Outline drawing of the pressure electrostatic generator.

vacuum tube. Protons, deuterons, or alpha particles, released at the top, are accelerated in their travel down the tube and bombard the desired target to produce artificial radioactivity or to effect transmutations.

5-11. The Cyclotron and Betatron

Slightly more than a decade ago E. O. Lawrence developed the *cyclotron*, a device that accelerates ionized particles by giving them a group of periodic impulses as they travel within two cylindrical sections of an evacuated chamber. The cutaway view, Fig. 5-32, shows an electromagnet arranged to contain the acceleration chamber between its pole faces. Two hollow, semicircular, D-shaped electrodes, slightly separated from each other

and insulated, are mounted in the chamber and connected to a high-frequency vacuum-tube oscillator. An electron emitter is located at the center of the chamber and arranged so that it causes ionization of a small quantity of hydrogen, deuterium, or helium which may be injected at that point.

A positively charged particle, liberated at the center, is drawn into the momentarily negatively charged electrode and because of the magnetic field assumes a circular path. At the moment it

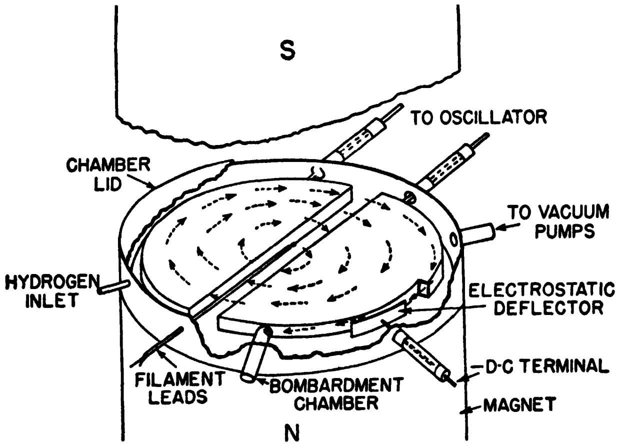


FIG. 5-32. Cutaway view of the acceleration chamber of a cyclotron showing the relation of the acceleration electrodes, magnetic field, and path of the charged particles.

emerges the polarity between the electrodes changes and another semicircular excursion takes place. The electric field in the meantime accelerates the ion, and the circular path is modified into a spiral path of gradually increasing diameter until the particle finally emerges from an opening at the edge of one of the electrodes. The final energy resident in the ion is equal to the energy acquired in passing from one electrode to the other multiplied by the total number of passages between them. Even though individual ions within the chamber travel longer or shorter paths, depending on their distance from the center, all reach the edge of an electrode at the same time, and, therefore, for a given magnetic field intensity, the impulses on each ion can be synchronized with the frequency of the oscillating electric field. The time t required for an ion to move through the semi-

circular path of one electrode is

$$t = \frac{\pi r}{v}, \tag{5-6}$$

where r is a particular radius, and v is the velocity.

The mechanical deflecting force of an ion having a charge e and moving at a velocity v in a constant magnetic field of intensity H is equal to Hev. The centripetal force of the ion of mass m, which has a value of mv^2/r, is equal to the deflecting force, or

$$\frac{mv^2}{r} = Hev. \tag{5-7}$$

From this we see that

$$r = \frac{mv}{He} \tag{5-8}$$

and that r and v are directly proportional; that is, an ion traveling in an outer orbit has a greater speed than one nearer the center. Substituting the value for r/v in Eq. 5–6, we obtain

$$t = \frac{\pi m}{He}, \tag{5-9}$$

which gives the value of t as independent of the radius of the path.

Magnetic field intensity and the radius of curvature govern the velocity. The kinetic energy W in joules residing in an ion of mass m kilograms as it leaves the acceleration chamber at a radius r meters is

$$W = \frac{1}{2}mv^2 = \frac{1}{2}\frac{m\pi^2r^2}{t^2}. \tag{5-10}$$

The first cyclotron had magnetic pole faces 5 inches in diameter, and a later model was then constructed with this dimension increased to 28 inches. The latter, built around a 75-ton magnet, was able to produce 10 microamperes of deuterons at an energy of 4,000,000 electron volts. Dimensions and output of subsequent cyclotrons were still further increased, and in 1948 a huge device containing an electromagnet with pole pieces 184 inches in diameter and weighing about 4000 tons was constructed. With a 50-kilovolt potential across the acceleration chamber this cyclotron is able to accelerate deuterons to energies of 200,000,000

electron volts and alpha particles to twice this amount. This energy enables the particles to penetrate the nuclei of atoms, causing nuclear fragmentation and the generation of cosmic rays. The acceleration chamber is illustrated in Fig. 5–33, and a view of the device, which provides an index of the size of the electromagnet, is shown in Fig. 5–34. The rotating capacitor,

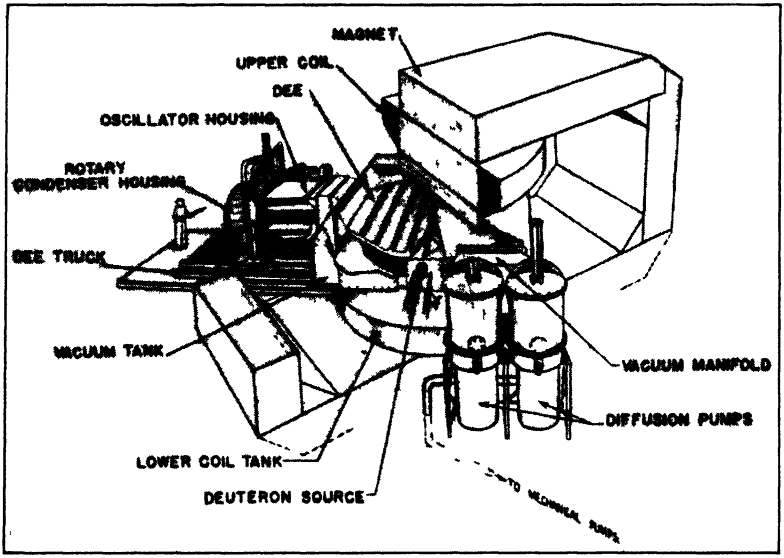


FIG 5–33. Cutaway view of the 184-inch cyclotron showing interior arrangement of the equipment. *Courtesy University of California Radiation Laboratories.*

by producing a varying capacity at a modulation rate of a few hundred times per second, varies by about 20 per cent the oscillator frequency, which is in the neighborhood of 10 megacycles per second. This feature makes possible the circumvention of the limitations imposed by the relativistic effect, which are encountered at high velocities, and permits the acceleration of particles to very high energies. From this method of operation is derived the term *frequency-modulated cyclotron* or *synchro-cyclotron.*

When beryllium is bombarded with high-speed deuterons, the beryllium disintegrates into boron, and neutrons are liberated which, in turn, may be used to bombard other substances. A net

result of bombardment by various particles, including neutrons, has been the production of more than 350 radioelements or isotopes during the last decade. A typical example is provided by radiophosphorus ${}_{15}P^{32}$, which can be produced by bombarding ${}_{16}S^{32}$ with neutrons, ${}_{15}P^{31}$ with deuterons, or ${}_{14}S^{29}$ with alpha particles. Radiophosphorus emits only beta particles, its



FIG. 5–34. Photograph of the 184-inch cyclotron. *Courtesy University of California Radiation Laboratories.*

half-life is 14.3 days, and the end product is the stable element sulphur ${}_{16}S^{32}$. Since a radioactive isotope is chemically identical to the ordinary element of the same atomic weight, it may be used as an economical substitute for radium in medical radiation treatments or as a tracer element. For example, a small quantity of an artificially produced soluble radioactive element may be added to a stream of water and the exact flow may be subsequently traced by determining the presence of the emitted particles or rays.

A new instrument, termed a *betatron*, has been constructed, which produces electromagnetic radiations of even greater pene-

trating power than the X rays emitted by the 2,000,000-volt unit described in Sec. 5–7. This electron accelerator, originally developed by D. W. Kerst, is built similar to a transformer and contains a laminated magnetic circuit with pole faces and magnetizing coils designed for low-frequency a-c operation. A



FIG. 5–35. The 100,000,000-volt induction electron accelerator or betatron. Diameter of circular vacuum tube, 6 feet. *Courtesy General Electric Company.*

glass tube, composed of sectors made with a conducting layer of silver on the inside to prevent the disturbing effect of accumulated charges and cemented together, is located within a larger doughnut-shaped vacuum tube mounted between the pole faces. An electron gun projects into the inner tube and emits electrons which are accelerated uniformly and move in a spiral path during that portion of the cycle when the magnetic field is in the proper direction. At the end of their travel, they strike a target and produce electromagnetic radiation.

In the 100,000,000-volt model, shown in Fig. 5–35, the electrons gain about 400 electron volts for every excursion around the

tube and are accelerated almost to the speed of light. The resulting electromagnetic radiation of extremely short wavelengths lies in the range of gamma and cosmic rays.

5-12. The Mass Spectrometer

The *mass spectrometer* is an instrument wherein a gas is ionized and segregated into streams of different masses which are meas-

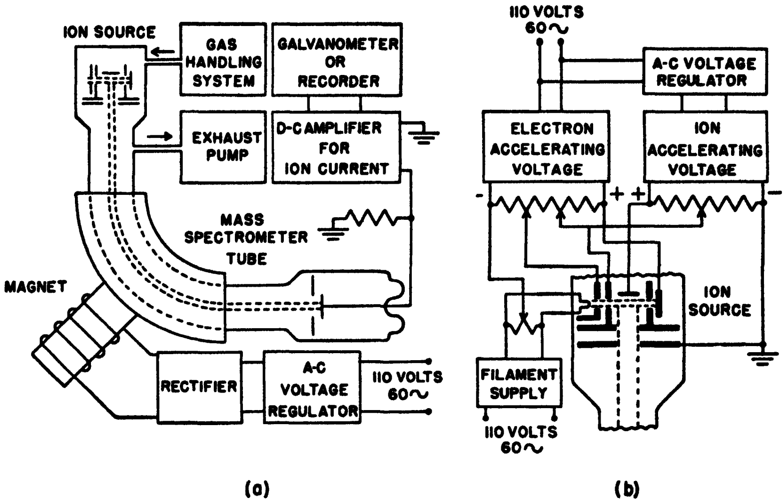


FIG. 5-36. (*a*) Simplified sketch and block diagram of the mass spectrometer; (*b*) details of the voltage supply for the ion source.

ured both qualitatively and quantitatively. Chemical analysis by the separation of positive ions is not new. It was proposed and used by J. J. Thomson many years ago, but more recent developments, such as simplified methods of obtaining a high vacuum, high-gain amplifiers, and unusually well-regulated a-c and d-c voltages, have aided in converting this purely scientific device into an important analytical production instrument in the petroleum, tire, and general chemical industries.

A small quantity of the gas to be analyzed in the mass spectrometer passes through the end portion of a high-vacuum tube and is ionized by electrons emitted from a heated filament, as indicated in the simplified sketch of Fig. 5-36. The ions are accelerated by an electric field, pass through a slit in the anode, and are then made to travel in a circular path through the action

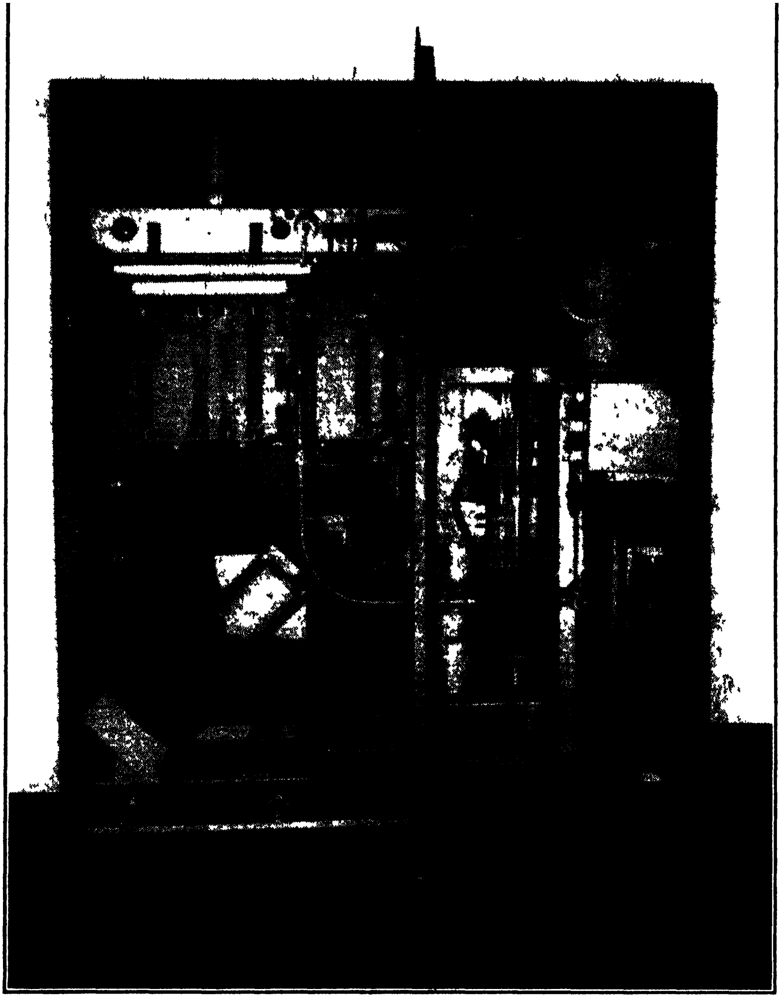


FIG. 5-37. View showing internal construction of the mass spectrometer. Note adjustment feature for the magnetic field at the lower left. *Courtesy Westinghouse Electric Corporation.*

of a magnetic field. Specific ions, having been deflected a definite amount, pass through an exit slit near the end of the tube, strike a plate, and give up their charge. This charge is amplified, and its magnitude is a direct index of the number of ions that reach the plate. For a certain magnetic field intensity

and a given accelerating voltage, the mass of an ion determines whether it passes through the exit slit or strikes the conducting side wall of the tube. Ions of light mass follow a path with a small radius of curvature; those with a heavier mass follow one with a larger radius. By changing the fields the successive ion

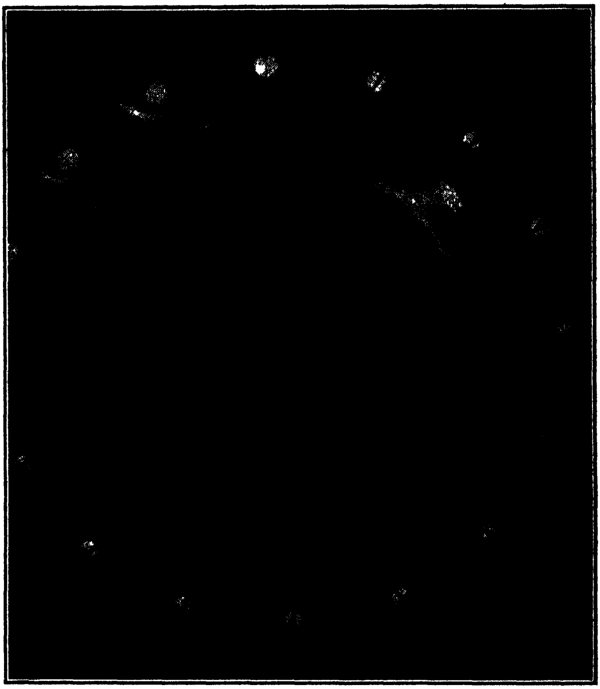


FIG. 5–38. View of the mass spectrometer in operation sorting molecules of different masses. *Courtesy Westinghouse Electric Corporation.*

streams of different masses are made to strike the target electrode, and their charges are measured after amplification. Figure 5–37, which illustrates the internal construction of the instrument, shows how the magnetic field can be changed simply and easily.

The instrument is calibrated by passing a mixed gas of accurately known proportions through the tube, adjusting the fields so that each component in succession is focused on the exit slit, and the current for each fraction is measured. Only one composition needs to be analyzed, and from this, extensions may be

made in the calibration to cover mixtures of various proportions. Extremely minute quantities of any substance in a mixture may be detected; determinations of as little as 1 part of oxygen in 10,000 parts of nitrogen are well within the range of the instrument. In a complex molecule, such as normal butane, containing a large number of component atoms, many masses are present and the entire *mass spectrum* may be determined both qualitatively and quantitatively. Figure 5–38 is the striking illustration of a mass spectrometer sorting molecules of three different masses.

Detection of vacuum leaks becomes very much simplified if gas from the evacuated system is passed through the spectrometer. A tiny jet of helium gas is played over any suspected area, and, with proper adjustment of the fields of the spectrometer for helium determination, any leak is indicated quickly on the output meter. The instrument registers as little as 1 part of helium in 400,000 parts of air at an operating pressure of 0.3 micron of mercury.

Problems

1. The ring-type grid-seal tube shown in Fig. 5–1 is commonly mounted with the grid ring in direct contact with the chassis or ground. Review the basic circuits of oscillators, Figs. 3–19(*a*) and (*b*), and make a circuit drawing of a grounded-grid oscillator.

2. What factors govern the length of the drift space in an ordinary klystron? The ratio of the energy stored to the energy lost per cycle defines the Q of a resonant circuit. What in your opinion is the best shape of a cavity for the highest value of Q?

3. Tabulate the common points of similarity in the functional and structural designs of the klystron, magnetron, and resnatron.

4. If an electronic transducer tube were designed with a fixed cathode and a single movable anode, how would the anode current vary with respect to the displacement of the anode?

5. Draw a circuit diagram of a vacuum-tube acceleration pickup, having two movable anodes, which is connected to a Wheatstone bridge input circuit operating into a single-stage amplifier.

6. Refer to the list of references on page 501 or other source information and draw a diagram of the electromagnetic spectrum. Indicate the various types of electromagnetic radiation in bands and give their limiting frequencies and wavelengths.

7. In Fig. 5–20, what is the relationship between the length of the line P_1P_2 and the length of NP_3 for the condition that the reflected waves are in phase? Prove your contention geometrically.

8. Tubes V_3 and V_4 in the circuit of Fig. 5–26 are shown as gas-filled

tubes. What advantages, if any, do these tubes have over vacuum tubes in this specific circuit?

9. A cyclotron is equipped with a magnet having pole faces 28 inches in diameter. The acceleration chamber has a diameter of 22 inches and is connected to a 20,000-volt 10-megacycle oscillator. The field intensity is adjusted to accelerate hydrogen nuclei, which have a mass of 1.66×10^{-27} kilogram. What is the kinetic energy of the bombarding ions in equivalent electron volts?

10. In the mass-spectrometer circuit, Fig. 5–36, explain in detail the necessity for (*a*) the alternating voltage regulator in the magnet supply circuit, and (*b*) the alternating voltage regulator in the ion-accelerating voltage supply circuit.

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6.

Gas-filled Tubes

Gas-filled tubes contain an atmosphere of an inert gas or mercury vapor, and because of this they are endowed with characteristics entirely different from those of the previously discussed vacuum tubes. The latter have a high and variable tube resistance, a relatively small anode current, and a grid that exercises complete control over the anode current; gas-filled tubes have a very low and nearly constant tube resistance, an anode current limited only by the load impedance, and grid control confined only to the initiation of the current flow through the tube. The response time of gas-filled tubes is much slower than that of vacuum tubes; nevertheless, it is extremely rapid compared to the half-period of a standard a-c power supply. Therefore, the peculiar characteristics of gas-filled tubes cause them to find their greatest application as switching devices in power circuits. We shall consider some of these tubes that range in size from small measurement and flash tubes to the large metal-enclosed units that are an important part of central-station and power-plant equipment.

6–1. The Geiger Counter

Some of the properties of gas-filled tubes were mentioned in Sec. 1–6. Factors that determine ionization and consequent conduction in a gas diode are the shape, composition, and placement of the electrodes, the nature and pressure of the gas, the operating temperature, and the value of the applied voltage. In 1908 H. Geiger developed a simple cold-cathode gas-filled tube which depends on an external source of ionized particles or ioniz-

ing radiation to initiate a current flow within the tube. Early tubes were erratic in their action, and later Geiger with A. Müller improved the design and stabilized the performance. Basically, a *Geiger-Müller tube* consists of a gas-filled envelope which contains a cylindrical cathode that surrounds an axially ar-

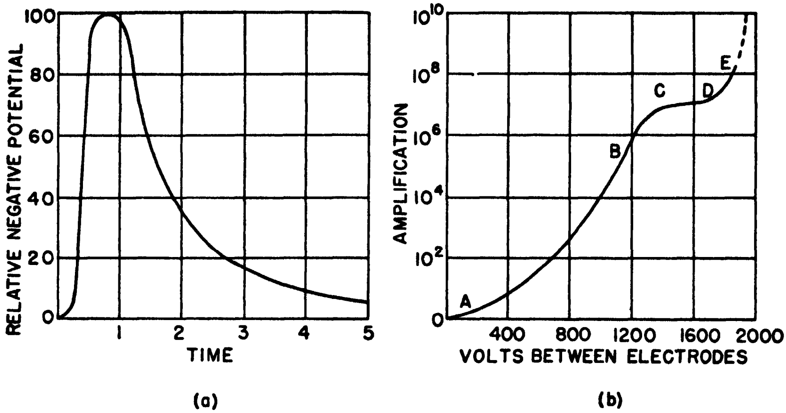


FIG. 6–1. Characteristics of a Geiger-Müller tube. (*a*) Pulse curve; (*b*) amplification curve.

ranged fine wire anode. Either a thin glass or metal window permits the entry of the ionizing particles or radiation. The operation depends on the formation of one or more ion pairs. Each liberated electron, in turn, produces other ions that cause a momentary change in the potential and a voltage pulse across

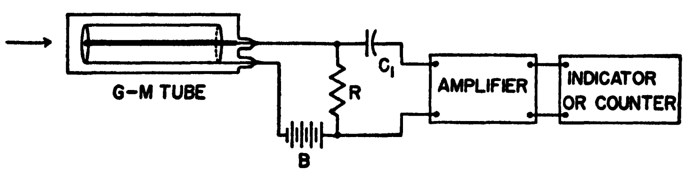


FIG. 6–2. Schematic sketch and simplified diagram of a Geiger counter.

the terminals of the tube. Structural or circuit means quench the discharge after an event and restore the tube to its original nonconducting condition.

The general characteristics of a Geiger-Müller tube are shown in Fig. 6–1; a schematic sketch and simplified circuit of a Geiger counter are given in Fig. 6–2. It will be noted from the voltage

characteristic that no ionization occurs with a low voltage applied to the tube, but when the voltage is increased the electrical field within the tube imparts sufficient energy to the electrons so that ions are formed. Throughout the voltage range *A–B*, each original electron causes the formation of successive ion pairs within a few thousandths of an inch of the surface of the central wire. The dissociated electrons reach the anode quickly, but the heavier positive ions require a much longer time before they reach the cathode, and, consequently, a positive ion sheath is formed around the anode. As the positive ions move toward the cylindrical cathode, the wire becomes more and more negatively charged until the potential reaches a maximum value, as shown in Fig. 6–1(*a*). The magnitude of the voltage pulse in the proportional region *A–B* is a function of the number of the original ionizing particles or the quanta of the ionizing radiation. After the voltage between the anode and the cathode, including the interelectrode capacitance *C* between them, has reached its maximum value, it decreases exponentially by leakage of the charge through the resistor *R*, the rate being determined by the time constant *RC*. The potential difference between the cathode and the anode is ultimately restored to its original value, but in the meantime the voltage pulse or count has been transmitted through the capacitor C_1 to the indicator.

With a still higher applied voltage, the field between the electrodes causes dissociated electrons to ionize outlying gas molecules and also to produce ionizing radiation. Ionization becomes progressive, and the gradually lowering field strength between the electrodes soon reaches a point where ionization can no longer be maintained. In the meantime a voltage pulse, essentially similar in shape to those produced throughout the proportional region but with a practically constant amplitude irrespective of the magnitude of the initiating stimulus, is produced. A tube operated within this voltage range *C–D* of the curve is termed a Geiger counter. If still higher voltages, indicated at *E* on the voltage curve, are applied to the tube, continuous discharge takes place.

Ordinarily tubes are filled with a gas, such as argon or krypton, at pressures which range from about 100 millimeters of mercury to nearly atmospheric pressure. In some designs the gas mixture is modified by the addition of several per cent of oxygen, and

often a small quantity of a complex gas or vapor, such as ethyl alcohol, is added to assist in obtaining self-quenching action. Envelopes for Geiger-Müller tubes are made of glass or metal, and the windows are designed for the specific use. For instance, a thin Lindemann glass window, which has a high transparency for radiation within the wavelength range of 0.5 to 2.2 angstrom units, is commonly used in X-ray diffraction work. Tubes are also made with windows of beryllium or thin sheets of mica; these are necessary for the transmission of the longer-wavelength X rays. A monochromatic X-ray beam composed of the K radiations, emitted by a copper, cobalt, iron, or chromium target, is almost completely absorbed in its passage through an argon-filled tube, while krypton acts similarly for the major K radiation emitted by a molybdenum target. These tubes are capable of detecting in excess of 3000 X-ray quanta per second, and form the foundation for an intensity meter since the number of quanta is a function of the intensity of X radiation.

An important analytical and research instrument known as a Geiger-counter X-ray spectrometer is obtained by combining such a tube with X-ray diffraction equipment. Early Geiger-counter spectrometers were arranged so that the tube, mounted on a pivoted arm, scanned the arc normally covered by the film and indicated the relative intensities of the diffracted X rays. In a more recent model, illustrated in Fig. 6–3, specimen and counter rotate about a common axis; the specimen holder rotates at one-half the angular velocity of the counter scanning arm. The scale is calibrated from 0° to 90°, and mechanical precision permits a dial micrometer to indicate accurately angles as small as 0.01°. The recording meter in the Geiger-counter output circuit not only registers the presence of the diffracted X rays but also measures their intensity. Frequently, only an indication from a single line is required for inspection or production control, and, therefore, scanning in those cases can be confined to observations within a few degrees. Applications of the instrument include such diversified uses as the identification of silicates and phosphates in boiler scale, checking of the composition of clays and other raw materials, and the rapid determination of high-molecular-weight organic materials, such as cholestorol and rotenone.

A Geiger-Müller tube can also be made to respond to neutrons

by filling it with boron trifluoride gas. If the nucleus of a boron atom is bombarded by a neutron, an alpha particle is released, and this, in turn, initiates the ionization within the tube.

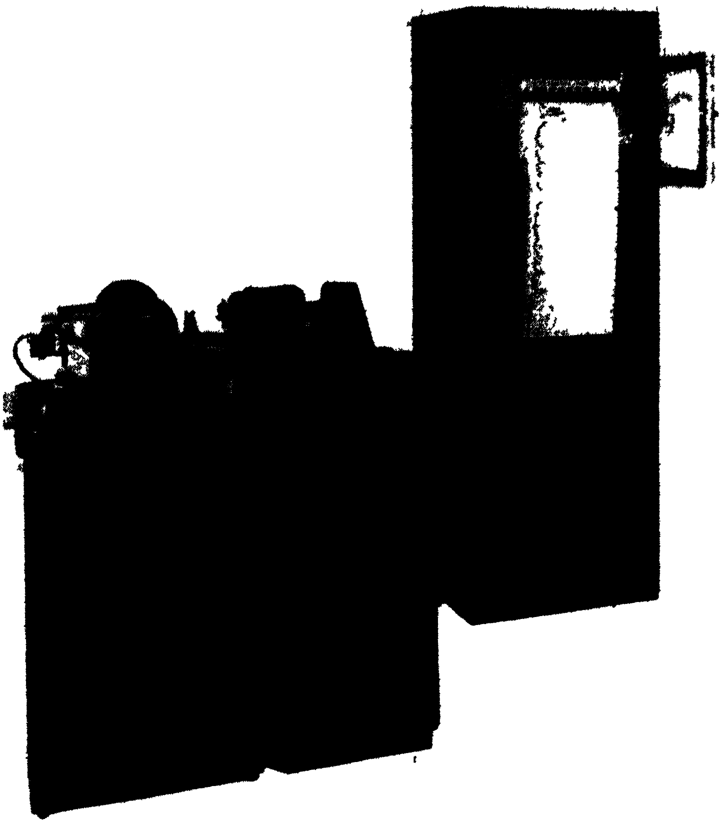


FIG. 6–3 Geiger-counter X-ray spectrometer with automatic recorder. *Courtesy North American Phillips Company, Inc.*

6–2. Flash Tubes

In 1932 H. E. Edgerton and K. J. Germeshausen developed the first of a number of tubes and circuits that operate on the principle of slowly charging a capacitor to a high voltage and then at an appropriate time applying an ionizing stimulus that causes

the capacitor to discharge through the tube within an extremely short period of time. Tubes of this type are known as *flash tubes* because the discharge is accompanied by an intense lightning-like flash of light. A flash tube consists of a long helix of glass or quartz tubing, equipped with electrodes at each end, as shown in Fig. 6–4. It is filled with either mercury vapor or xenon. Helical tubing makes for compactness and by being enclosed within an outer bulb prevents breakage and provides safety in handling. In some designs one end of the helix is left open, with one electrode mounted within the outer envelope and with gas in both the helix and outer envelope.

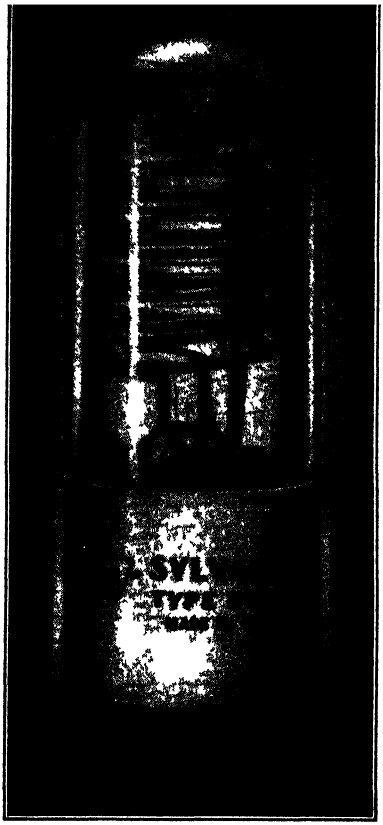


FIG. 6–4 A 400-watt-second flash tube used as a light source for high-speed photography Over-all length, 6½ inches; diameter, 2 $\frac{5}{16}$ inches *Courtesy Sylvania Electric Products, Inc.*

The flash-tube circuit, shown in Fig. 6–5, comprises two parts, the power supply and the flash gun. The power supply charges the large capacitor C_3 to a high voltage by means of the two rectifier tubes V_1 and V_2 which are connected in a voltage-doubler circuit. A wire or foil electrode, placed on the outside of the flash tube V_3 near the cathode, is connected to the secondary winding of an ignition coil T_2.

After the closure of switch S_1, the capacitor C_3 is charged to the high voltage and the capacitor C_4 is charged to about 60 volts by the voltage drop across the resistor R_2. When next the switch S_3 is closed, the charge on C_4 passes through the primary winding of transformer T_2, and the

resulting induced voltage in the secondary winding produces an electric field that ionizes the gas and initiates the capacitor discharge. The discharge current of the capacitor through the flash lamp reaches a maximum of several thousand amperes, and there is an intense blue-white flash of light. Peak light output for the discharge of a 120-microfarad capacitor, charged to 2500 volts, is about 48,000,000 lumens, and the effective flash duration is approximately 200 microseconds. A capacitor charging time of about 15 seconds is required between successive flashes. The

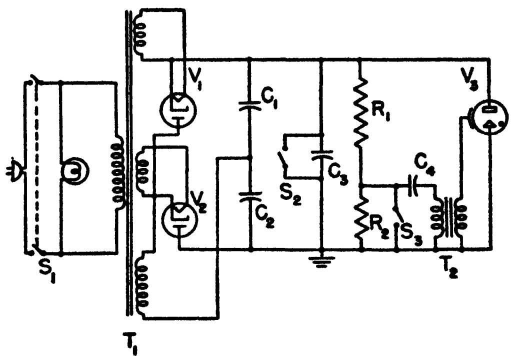


FIG. 6-5. Typical circuit for a flash tube.

tube has a long life; more than 10,000 flashes may be obtained under normal operating conditions. High operating voltages demand good insulation, and a switch S_2 is provided as a safety device to discharge the capacitor if the unit requires service or is removed from the case. A pilot light indicates that the apparatus is in an operative condition.

Although flash durations of several hundred microseconds are ample for arresting ordinary motions, exposures involving high speeds, for instance those of projectile flights, require illuminations of only a few microseconds. The flash time can be reduced by specially designed lamps and small capacitors charged to very high voltages. Equipment of this type is available which provides a high-intensity flash of only 2 microseconds. During that time an object moving at the rate of 1000 feet per second is displaced less than 0.01 inch.

Many obscure facts of nature become known when successive high-speed exposures are made of a motion sequence. The

startling effect of aerated water in clinging to a body is illustrated in Fig. 6–6. In passing through a faucet attachment, shown sectionalized in Fig. 6–7, screens divide the stream of water into jets and air is drawn in through side openings and is mixed with the water to produce the aerated water stream. The

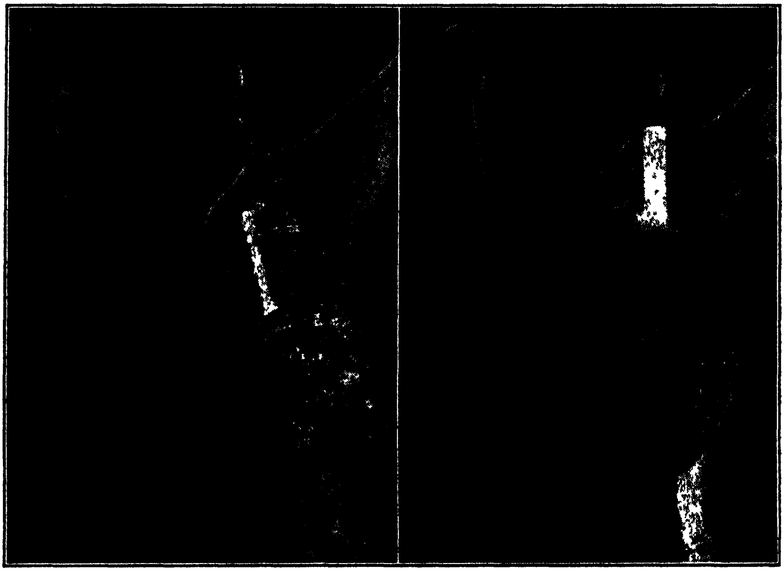


FIG. 6–6. (*a*) Water splashes when it flows from an ordinary faucet and hits glass; (*b*) water clings to glass when it flows from an aerator faucet. *LIFE photographs by Gjon Mili. Copyright TIME, Inc.*

explanation as to why aerated water clings to a surface, and normal water issuing from a faucet does not, is left to the reader.

6–3. Grid-glow and Trigger Tubes

An electrode or grid located in close proximity to the cathode within a gas tube may be used to start or prevent ionization. These cold-cathode tubes are termed *grid-glow* or *trigger tubes*. The typical construction, illustrated in Fig. 6–8(*a*), shows the cathode as an oxide-coated inverted saucer-like electrode through the center of which the wire anode projects from an insulated glass tube. A wire ring placed between the anode and the cathode acts as the control electrode. When a suitable mo-

mentary potential is applied between the grid and the cathode, ionization takes place between them and the discharge is transferred to the anode, provided that the anode is at a sufficiently high positive potential with respect to the cathode. If a pair of contacts on a relay in the anode circuit are connected so as to open the anode circuit after the relay is energized, the tube is restored to its original nonconducting condition.

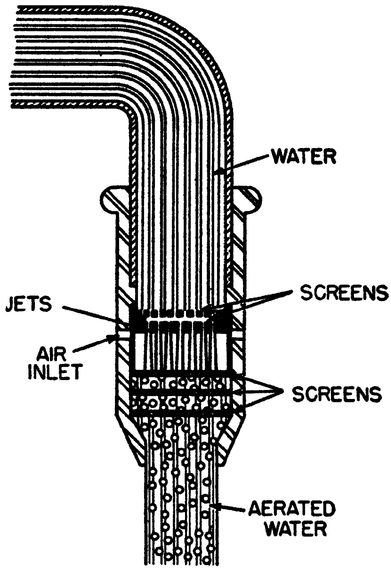


FIG. 6–7. Sectionalized view of an aerator faucet.

Breakdown may occur between any two electrodes of a grid-glow tube, and tubes are often operated with positive voltages on the grid, in which event there is a discharge and grid current flows. A critical anode voltage exists at which breakdown occurs with zero grid current, but when the grid voltage is increased so as to cause grid current, the critical anode voltage is reduced, as shown in the transition characteristic Fig. 6–9(*a*). At any anode voltage above the critical value, the discharge is transferred from the cathode and grid to the cathode and anode. The anode characteristic obtained with resistors in both grid and anode circuits, and connected to a 60-cycle supply line, is given in Fig. 6–9(*b*). It shows that the voltage drop across the tube remains practically constant over a considerable range, as it does in voltage-regulator tubes, and also that the tube can be used as a rectifier because of the asymmetrical shape of the curve.

The main discharge within a grid-glow tube is accompanied by emission of light. A tube of this general type for use as a stroboscopic light source, and known as a *strobotron*, was developed by K. J. Germeshausen and H. E. Edgerton. It consists of a neon-filled tube containing a cold cathode coated with a

low-work-function material. As shown in Fig. 6–8(*b*), a control grid and a screen grid are located between the cathode and the

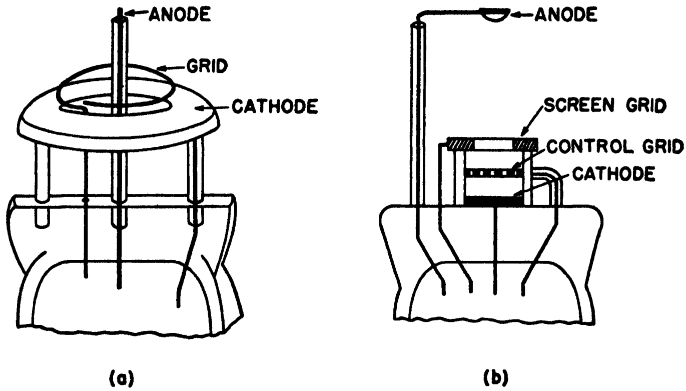


FIG. 6–8. Views showing location and arrangement of the electrodes in a (*a*) grid-glow tube; (*b*) strobotron.

anode and are so arranged that the cathode is completely shielded from the anode by the screen grid. During operation, a capacitor, periodically charged to a voltage greater than the breakdown

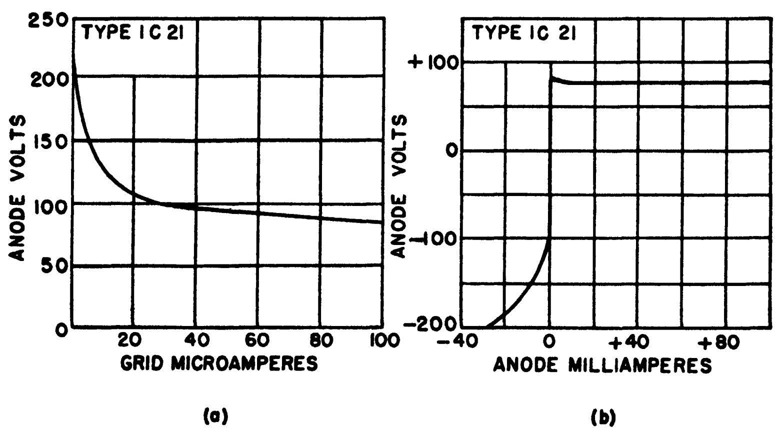


FIG. 6–9. Characteristics of a grid-glow tube. (*a*) Transition characteristic; (*b*) anode characteristic.

voltage, is connected between the cathode and the anode, and voltages are applied to the grids to prevent breakdown. When the potential between the two grids reaches a critical value,

ionization of the gas takes place, the initial discharge between the grids transfers itself to the cathode and the anode, and the capacitor discharges with a resulting brilliant flash of light. The frequency of the flashes is readily controlled over wide limits, the maximum being about 240 pulses per second.



FIG 6–10 Side view of the Strobotac showing details of the control panel. Readings are taken from a drum-type scale at the top of the instrument. *Courtesy General Radio Company.*

6–4. The Strobotac

The *Strobotac,* illustrated in Fig. 6–10, consists of a portable instrument incorporating a strobotron tube, a power supply, and a multivibrator. The instrument, during use, is directed so that a periodic illumination is thrown on a rotating or vibrating object under observation. A multiposition switch permits the selection of low or high flashing rates, triggered either by the variable-

frequency multivibrator or by an external contactor, an off position, or a position at which the flashing rate occurs in synchronism with the power-supply frequency. The flashing rate of the multivibrator, which may be varied between the limits of 600 and 14,400 flashes per minute, can be ascertained from the scale just above the frequency adjusting dial. The instrument is calibrated for the two ranges by checking the illumination on a

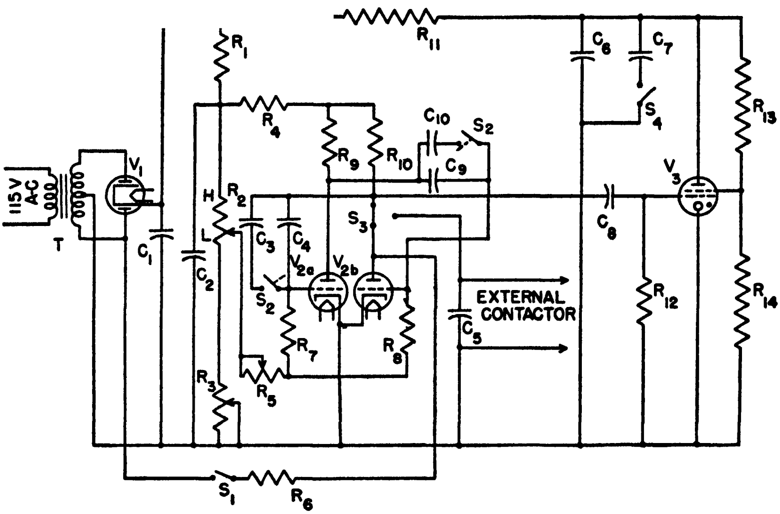


FIG. 6–11. Simplified circuit of the Strobotac.

line-frequency-operated vibrating reed located near the tube and then adjusting the flashing rates until the reed appears motionless.

The circuit diagram of the instrument, Fig. 6–11, may be divided into three portions: the d-c power supply obtained from the rectifier tube V_1, the multivibrator centered around the twin triode V_{2a} and V_{2b}, and the strobotron V_3. The rectifier charges the capacitor C_6 through the resistor R_{11}, and this voltage is impressed between the anode and the cathode of the strobotron. The tube, however, cannot conduct until ionization takes place between the two grids. The screen grid is given a positive potential with respect to the control grid, which is at cathode potential, by being connected in the voltage-divider circuit R_{13} and R_{14}, but this potential is not sufficient to cause ionization. Each time the triode V_{2b} conducts, or if the switch

S_3 is thrown to the external contactor and its terminals are short-circuited, the capacitor C_8, which is charged to the rectified voltage through resistors R_1, R_4, R_{10}, and R_{12}, discharges through R_{12} and reduces the potential at the control grid to a sufficiently negative value so that ionization occurs between the two grids. This, of course, produces the main discharge of

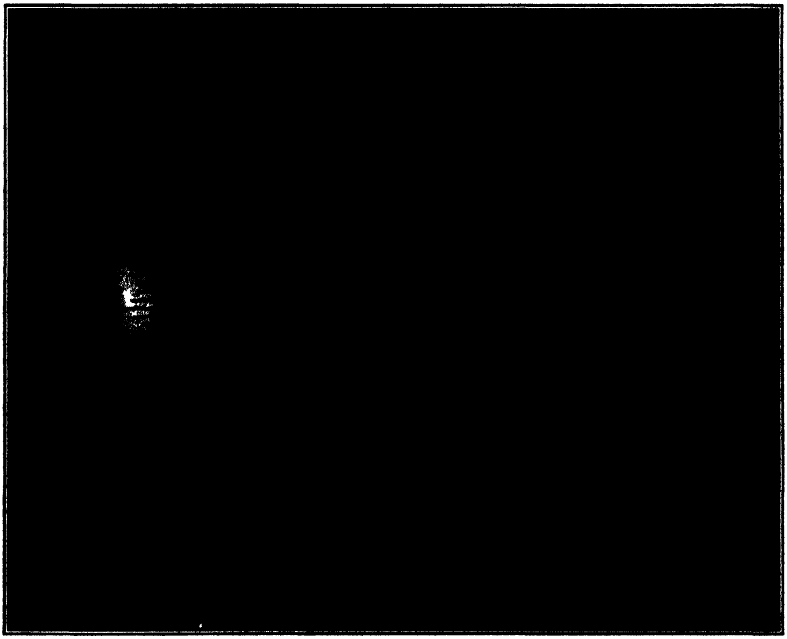


FIG. 6–12. Photograph of a multiple-flash exposure of the timing marks on a gasoline-engine flywheel taken with stroboscopic light. *Courtesy General Radio Company.*

capacitor C_6 and results in a flash of light. During the time C_6 recharges, the open-circuit condition for C_8 is re-established, it too is recharged, and the original condition is restored. Switch S_4 connects an additional capacitor C_7 in the main discharge circuit when the instrument is used on low flashing rates; the added capacitance causes a more intense flash of light and makes the illumination the same for low and high flashing rates.

The multivibrator circuit is in general similar to the one shown in Fig. 3–30. The rate of discharge of capacitors C_4 and C_9 through the dial-operated potentiometer R_2 controls the oscilla-

tion periodicity for high flashing rates; the two switches, labeled S_2, connect capacitors C_8 and C_{10} in parallel with C_4 and C_9, respectively, for low flashing rates. Calibration adjustments are made by altering the values of resistors R_3 and R_5.

The Strobotac is perhaps best known for its application as a tachometer and for its use as an exploring tool in vibration analysis. If the speed of a motor rotor or other rotating object varies enough to make a steady image difficult to obtain, the external contactor may be connected to a cam arrangement on the rotating shaft, and, since the flash occurs at the moment when the leads are short-circuited, a steady image results. For instance, the occurrence of the spark in an automotive or airplane engine cylinder can be accurately timed, as shown in Fig. 6–12, by attaching a wire to the spark plug and impressing the ignition voltage on the secondary winding of an ordinary ignition coil, the primary winding of which is connected across the external contactor. The induced voltage in the primary winding initiates the discharge, and the ensuing light flash discloses the angular position of the fly wheel at the instant when ignition takes place.

6–5. Thyratrons

A gas-filled tube with its low internal resistance, requires that the anode current be limited, and the anode voltage must be reduced below the ionization voltage of the gas to interrupt the current flow. A capacitor discharging through a cold-cathode flash tube causes a large anode current to flow because of the absence of a load resistance, but the discharge is also confined to a very short interval during which the capacitor voltage drops to a value no longer able to maintain ionization. To increase the average output of a gas-filled tube, it is necessary to use either a thermionic or a mercury-pool cathode to supply the requisite number of electrons; to exercise firing control requires the introduction of a control grid. The *thyratron*, developed by A. W. Hull and his associates, consists of a hot-cathode gas-filled tube in which one or more electrodes are used to control electrostatically the initiation or starting of a unidirectional current flow between the cathode and the anode.

Cathode and anode constructions for gas-filled tubes were described in Secs. 2–5 and 2–6. Precautions are taken in the design to prevent uncontrollable ionization by enclosing the

leads within the tube and by surrounding the cathode or anode, or both, with a metallic shield. This isolates these electrodes except for one or more openings in the grid through which the normal discharge takes place. Sectionalized views of a simple three-electrode thyratron and one incorporating a shield grid in addition to the control grid are shown in Fig. 6–13. In the shield-grid thyratron both cathode and anode are placed in separate compartments within the shield structure, and an aperture in the

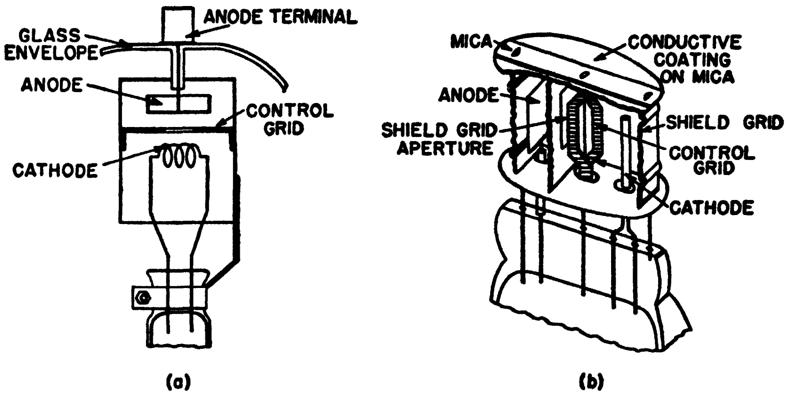


FIG. 6–13. Sectionalized views of (*a*) a three-electrode thyratron; (*b*) a shield-grid thyratron.

shield partition provides an opening for the discharge. Figure 6–14 illustrates two hydrogen-filled thyratrons which are characterized by the advantages of low ionization times and high peak currents.

A simple thyratron circuit has a load resistor in the anode circuit and a relatively high-valued resistor in the grid circuit. The grid-circuit resistor is used because positive ions move toward the negatively charged grid during discharge, and this results in a grid current. For a given direct or alternating peak anode voltage, the grid potential of a specific thyratron must be reduced to a critical value before the tube conducts or fires. This is demonstrated in Fig. 6–15(*a*). A number of control curves, taken at various temperatures, are given because the tube is temperature sensitive, being filled with mercury vapor; the companion curve Fig. 6–15(*b*) is obtained from a thyratron filled with an inert gas and designed for a lower operating voltage. Any grid voltage to the right of a given control curve causes the

tube to fire. Increasing the grid voltage to a more negative value while the discharge is in progress is ineffective in controlling or extinguishing the discharge because positive ions are attracted toward the grid, surround it, and form a positive-ion sheath. It is only after the anode voltage is reduced below the ionization value that the discharge ceases, the ions recombine to make

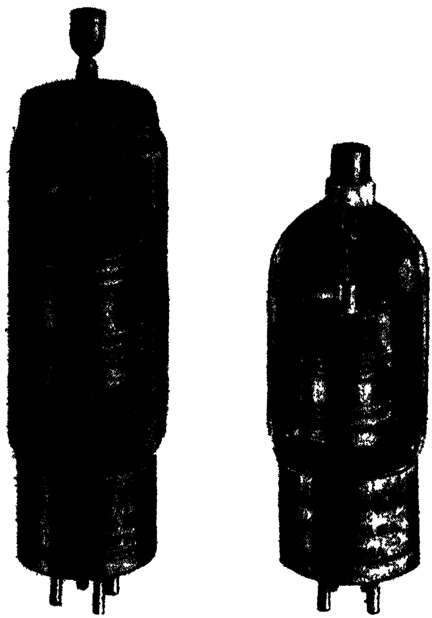
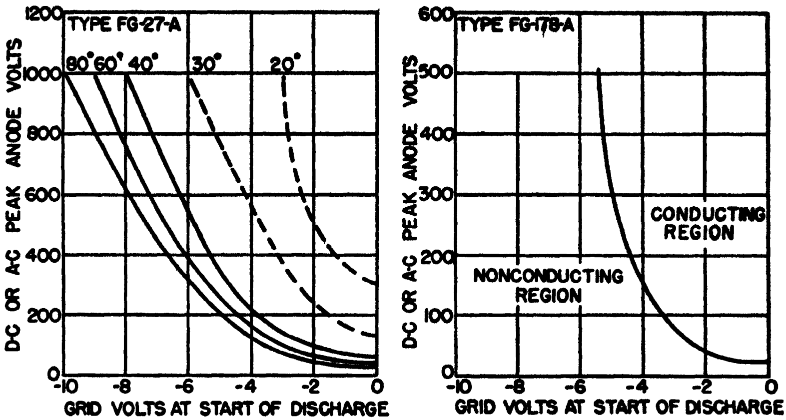


FIG 6–14. Two hydrogen-filled thyratrons designed for pulsing service at high repetition frequencies, high peak currents, and high voltages *Courtesy Sylvania Electric Products, Inc*

neutral atoms, and the grid loses its positive sheath, permitting it to regain control.

Ionization and deionization do not occur instantly; the time interval varies with such factors as the gas or vapor pressure, the ambient temperature, and the applied voltage. In general the ionization time extends over only a few microseconds, but the deionization time is much longer. In some tubes it extends over several hundred microseconds, and, therefore, thyratrons can be operated only on a-c circuits of relatively low frequencies. For the frequencies normally encountered in electric power applica-



(a) (b)

FIG. 6–15. Anode-voltage grid-voltage characteristics. (*a*) Thyratron filled with mercury vapor; (*b*) thyratron filled with inert gas.

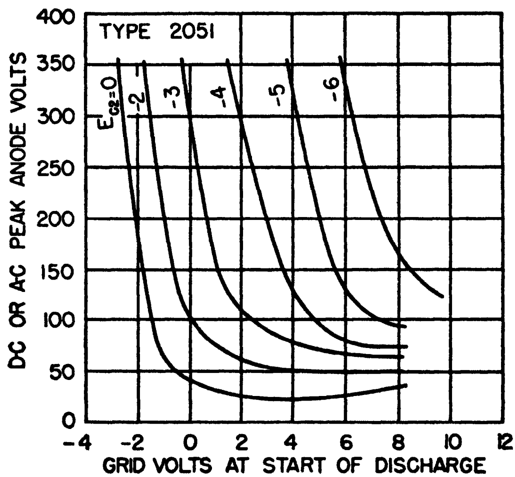


FIG. 6–16. Control characteristics of a shield-grid thyratron.

tions, ionization times of several microseconds are not very important, and the interval for deionization requires only a small portion of the time after the positive portion of the cycle drops below the ionization voltage and during the initial part of the negative portion of the cycle.

It must not be assumed that thyratrons are made to operate only with negative grid voltages; some are designed to fire when

the control grid reaches a definite positive potential with respect to the cathode, but tubes of this type are generally made with a shield grid. The control characteristics of a shield-grid thyratron filled with argon, given in Fig. 6–16, indicate that the voltage of the screen grid affects the critical voltage of the control grid.

If an a-c power supply is connected in the anode circuit of a thyratron, the instantaneous anode voltage varies sinusoidally.

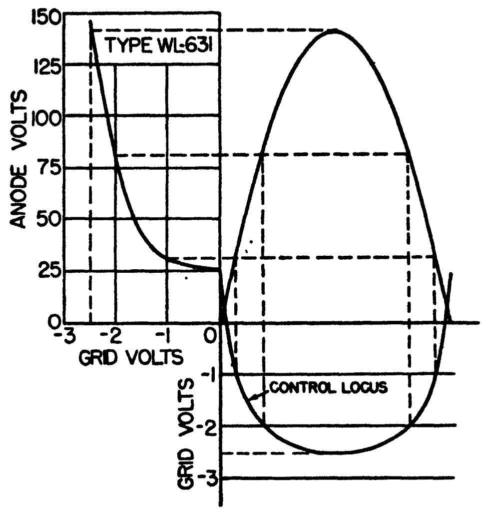


FIG. 6–17. Construction of the control locus for a thyratron from the grid control characteristic.

During the positive portion of the cycle the tube may or may not conduct, depending on the voltage of the control grid; during the negative portion of the cycle it cannot conduct, irrespective of the grid potential, since this involves electron flow from the anode to the cathode. A specific grid-control characteristic may be used in conjunction with the positive lobe of a sinusoidal voltage to construct the control locus, as indicated in Fig. 6–17, by determining the magnitude of the critical grid voltage required to prevent the tube from firing for various direct or peak alternating anode voltages and plotting these values below the anode-voltage lobe. The construction shows that the tube can conduct only if the grid voltage is less negative than the values given by the control locus. For example, if the tube whose control locus is

shown in the figure is supplied with a constant grid voltage of —3 volts no conduction occurs, but if the grid voltage is reduced to —2.5 volts the tube fires at the maximum anode voltage and continues to conduct to the end of the positive portion of the cycle. With a grid voltage of —2 volts, the discharge is initiated when the anode voltage is about 80 volts. In other words, the tube starts conducting at that positive anode voltage where the grid voltage intersects the control locus. Obviously, a direct grid voltage, or an alternating grid voltage if it is in phase with the anode voltage, can initiate conduction only during the first half of the positive voltage alternation. However, as we shall see in the next section, other methods and circuits have been devised to make the tube fire at any desired point within the half cycle. The control locus in the figure is drawn for the entire positive voltage lobe; that is, it covers 180°. Actually, of course, conduction through the gas or vapor takes place only when the anode voltage is in excess of the ionization potential of the particular gas or vapor in the tube.

6–6. Phase-shifting Methods

When an alternating voltage is supplied to the anode and a voltage in excess of the critical value to cause breakdown is applied to the control grid of a thyratron, the instantaneous anode current i_b in amperes during discharge is given by the expression

$$i_b = \frac{E_m \sin 2\pi ft - E_0}{R}, \tag{6–1}$$

where E_m is the maximum value of the applied voltage, f is the frequency in cycles per second, t is the time in seconds after beginning of the cycle, E_0 is the voltage drop across the tube, and R is the load resistance in ohms.

If the tube is operated on ordinary power circuits, the value of E_0 is quite small and for purposes of simplification is assumed to be zero in the following discussion of control circuits. This also postulates that the tube continues to conduct to the very end of a positive half-cycle instead of only to the phase angle determined by the ionization potential of the gas within the tube; for conduction throughout the entire half-cycle a similar, very small nonconducting interval at the beginning of the cycle is also neglected. Of course, in actual operation the value of E_0

is important and must be considered, particularly in efficiency calculations.

The problem of thyratron control resides in having the grid voltage intersect the control locus at any position throughout 180° while the anode is at a positive voltage. The average current I_{av} from the instant of conduction to the end of the half-cycle may be obtained by integrating Eq. 6–1 between limits of angles, during which the tube conducts, and dividing the result by the base. Thus, we get

$$I_{av} = \frac{E_m}{2\pi R} (1 + \cos \theta), \tag{6–2}$$

where θ, termed the *starting angle,* may vary between the limits of 0 and π radians. For full-wave rectification and control that uses two tubes, as will be shown in later circuits, the average rectified current is twice that given above and represents the direct current I_{dc} as indicated on a d-c ammeter, or

$$I_{dc} = \frac{E_m}{\pi R} (1 + \cos \theta). \tag{6–3}$$

This shows that, for given values of maximum alternating voltage and load resistance, the rectified direct current varies as the cosine of the starting angle; the numerical value of the quantity in the parentheses ranges between 0 and 2. The direct current varies almost linearly with respect to starting angles between 60° and 120°, and consequently thyratrons are widely used to operate and control d-c motors on a-c power sources.

A simple and very effective method of controlling the starting angle on an a-c operated thyratron consists in supplying the grid with an alternating voltage, the phase angle of which may be varied with respect to the anode voltage. The bridge circuit of Fig. 6–18(a) is one of a number of such circuits that have been devised to produce a phase shift of nearly 180°. The circuit utilizes a capacitor, which has a reactance X_C at the operating frequency, two fixed resistors, and a variable resistor. The corresponding voltage vector diagram is shown in Fig. 6–18(b). A suitable alternating voltage is impressed on the input terminals, and if, for convenience in analysis, the resistances of R_1 and R_2 are made equal, the output voltage V_2 is equal to one-half the input voltage V_1. As the resistance of R is changed from an

extremely high value to zero, the I_2R vector is turned counterclockwise and the angle ϕ, which represents the phase displacement between the output and the input voltages, increases from just beyond 0° to nearly 180°.

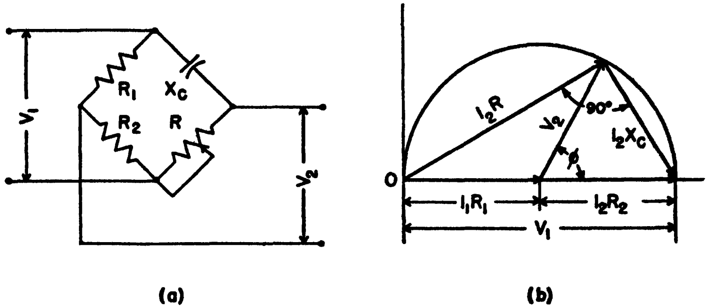


FIG. 6–18. (*a*) Bridge-type phase-shift control circuit; (*b*) corresponding vector diagram of voltages in the control circuit.

Resistors R_1 and R_2 are often replaced, as shown in Fig. 6–19(*a*), by a tapped transformer winding which also supplies the operating voltage. Resistor R_L represents the load in the anode circuit, and R_G is placed in the grid circuit to prevent

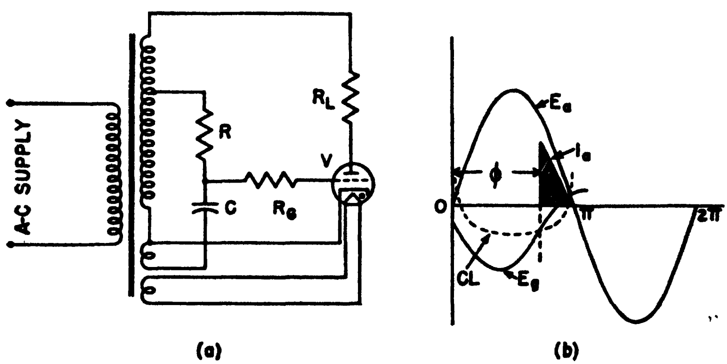


FIG. 6–19. (*a*) Modified phase-shift control circuit; (*b*) specific phase relationship between grid and anode voltages causing thyratron to fire late in half-cycle.

excessive grid current during the time when the grid is at a positive potential with respect to the cathode. With R at its maximum value, the phase angle of the alternating grid voltage is nearly 180° out of phase with the anode voltage and does not

intersect the control locus. As the value of R is reduced the phase difference between the anode and grid voltage is also reduced, as illustrated in Fig. 6–19(*b*), causing the grid voltage to cross the control locus, and a discharge occurs which continues to the end of the half-cycle. Gradual and continuous control of the thyratron firing position during nearly 180° of the positive half-cycle may be achieved by the variation of R. If R and C are interchanged, the anode and grid voltages are 180° out of phase with R at zero. When the value of R for this case is increased, conduction occurs at the beginning of the half-cycle and firing control cannot be obtained because the grid voltage always remains above the control locus.

Inductive reactance may be used instead of capacitive reactance in a bridge circuit to obtain phase shift. For instance, the capacitor C in Fig. 6–19(*a*) may be replaced with the variable resistor and R may be replaced with an inductor. As the value of the variable resistor is increased, the phase angle of the grid voltage is advanced from the out-of-phase position and the average current through the tube is gradually increased. As in the previous example, when these two circuit elements are interchanged, that is, when the inductor occupies the position held by the capacitor C, and if the variable resistor remains as shown in the diagram, the phase between the two voltages is retarded as the value of the resistor is decreased, the current reaches full value immediately, and control becomes impossible.

The crossover between the grid voltage and the control locus is steeper in some phase positions than in others. Clearly, the steeper the intersection between the two, the more definite the current-initiating position. Frequently circuits are encountered where the alternating grid voltage is superimposed on an adjustable negative direct voltage to obtain steep intersecting angles. In other circuits, a phase-adjustable steep-wavefront pulse lasting only a few milliseconds is used to initiate the discharge. The pulse is obtained from a peaking transformer of the magnetic-leakage type, shown diagrammatically in Fig. 6–20(*a*). One leg of the transformer core is made of Permalloy, and the grid excitation winding is placed on this leg. The Permalloy core reaches magnetic saturation early in each alternation, after which the magnetic flux finds a lower-reluctance path through the central portion of the magnetic circuit. Alternate positive and

negative voltage pulses of short duration are induced in the grid excitation winding during the time the flux passes through a small range near the zero values. In order to obtain a shift in the starting angle of the voltage pulse, a constant but adjustable magnetic flux is superimposed on the alternating flux by passing a direct current through control windings placed adjacent to the main transformer winding. As illustrated in Fig. 6–20(*b*), a constant magnetic flux in one direction produces a lag in the

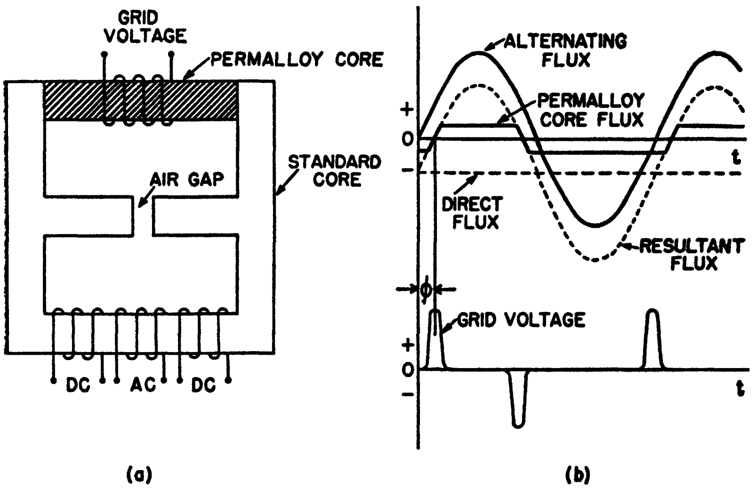


FIG. 6–20. (*a*) Sketch of a magnetic-leakage transformer; (*b*) waveforms of magnetic flux in core and induced voltage in excitation winding.

position of the voltage pulse, and a constant magnetic flux in the opposite direction causes an advance of the pulse with respect to the position it occupies when no constant flux is present in the core. The anode potential is obtained from a separate transformer, but, since the same power supply is used throughout, accurate phase control of the starting angle is readily obtained.

6–7. Thyratron Applications

A thyratron permits the passage of a large current, and consequently massive relays and circuit connectors can be used in the anode circuit. Since the anode current is interrupted at the end of each cycle of the power supply, and the grid, if sufficiently negative, resumes control, a thyratron circuit can be made to function as a timer throughout an integer number of

cycles. Thyratron timers are employed as switching devices, for sequence control, in welding equipment timing, in motor acceleration, and in process timing controls. A general-purpose timer is illustrated in Fig. 6–21. The thyratron is located in the center

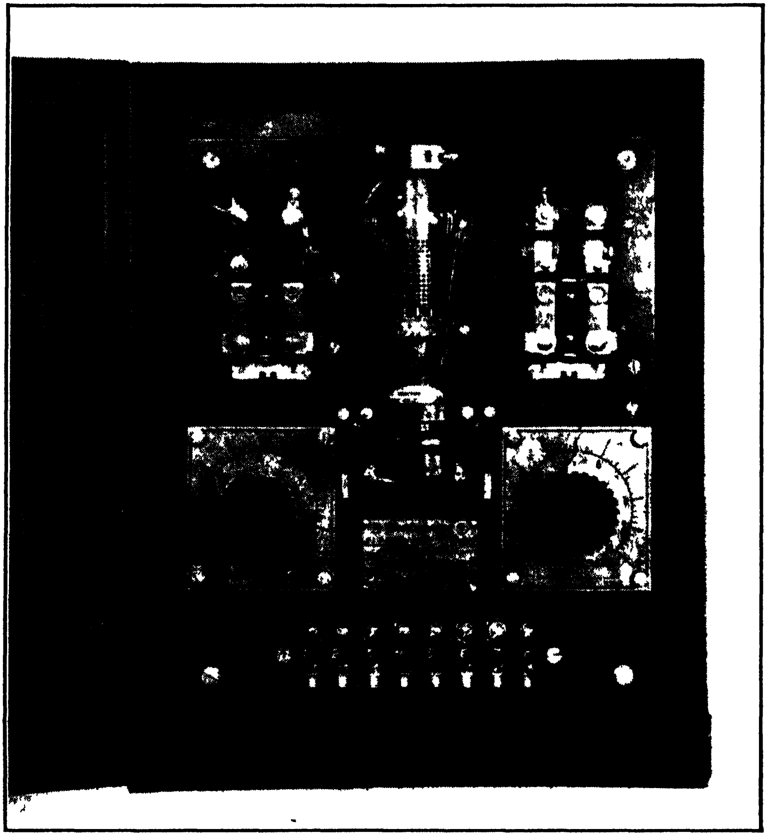


FIG. 6–21. View of a general-purpose timer with cabinet door open. *Courtesy Westinghouse Electric Corporation.*

of the panel between two relays, one of which is used for sequence operation and the other for control operations. Coarse and fine timing adjustment dials are located below the relays, and the transformer, capacitors, and other components are mounted on the back.

The timer circuit, Fig. 6–22, is of the type which opens or closes a circuit after a predetermined time interval following the

closure of the initiating switch. It operates on the basis of initially impressing a negative voltage on the grid and then applying an adjustable positive voltage, which causes the thyratron to conduct. The positive voltage is then gradually reduced, according to a preset rate, until grid control is again reestablished.

The circuit shows a transformer T, one winding of which supplies the filament of the thyratron V; a second winding

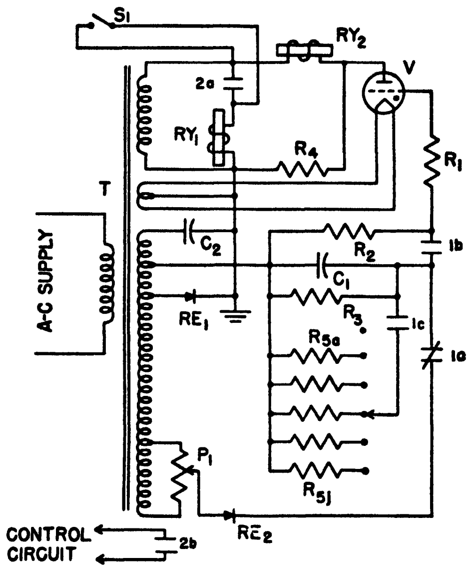


FIG. 6–22. Circuit diagram of the general-purpose timer.

provides the anode voltage and is responsible for the relay operation at the proper time; and a third winding, connected in the grid circuit, forms the basis of the timing control. As shown, the filament of the thyratron is energized and the dry-plate rectifier RE_1 has charged the capacitor C_2 to a negative voltage which prevents the thyratron V from conducting; it is impressed on the grid through resistors R_1 and R_2. A second dry-plate rectifier RE_2, operating in conjunction with an adjustable potentiometer P_1 and a transformer winding, charges capacitor C_1 through the normally closed relay contacts 1_a to a specific voltage. When the switch S_1 is closed, the relay RY_1 energizes; this closes contacts 1_b and 1_c and opens contacts 1_a. Opening of contacts 1_a

disconnects capacitor C_1 and removes the charging voltage. Closure of contacts 1_c connects the preselected resistance in parallel with capacitor C_1 and the extremely high-valued discharge resistor R_3. The closing of contacts 1_b connects the positive terminal of the highly charged capacitor C_1 to the grid of the tube. The tube conducts, and the relay RY_2 is energized. Relay contacts 2_a then close and maintain the current flow through RY_1 even though the initiating switch is opened. Contacts 2_b also operate and close the control circuit for the preselected interval.

Capacitor C_1 gradually discharges through the preset value of the resistance R_5. After a certain interval, depending on the original charge on C_1, that is, on the setting of the potentiometer P_1 and on the resistance R_5, the voltage across C_1 drops to a value at which the fixed negative voltage from the capacitor C_2 again assumes control at the end of a cycle of the supply voltage and the tube ceases to conduct. This causes relay RY_2 to de-energize, and the control circuit contacts 2_b open. Contacts 2_a also open the circuit to relay RY_1, which in turn restores its contacts to the normal inoperative position.

Resistor R_1 is a grid-current limiting resistor; the high-valued resistors R_2 and R_3 act as protective discharge resistors for capacitor C_1; and resistor R_4, which is connected in parallel to the relay RY_2, acts as a protective means to absorb the magnetic energy stored in the relay when the anode current is interrupted.

Over-all accuracy of the timer depends on variations in relay operation, on the characteristics of the capacitors, on the constancy of the other circuit elements, and on the tube. Intervals within $1\frac{1}{2}$ cycles are commonly obtained on a 6-cycle interval for a short timing period, whereas an accuracy of about 1 second or approximately 2 per cent may be obtained at the longer time intervals which may extend up to about 45 seconds.

The thyratron, like the gas diode, may be used as a relaxation oscillator. It is commonly applied in the cathode-ray oscilloscope to supply the time base where sweep frequencies up to about 50,000 cycles per second are required. In the basic thyratron relaxation-oscillator circuit, Fig. 6–23(a), the values of the capacitor C, the resistors R_2 and R_3, and the supply voltage E_B determine the oscillation frequency. The constant grid bias is adjusted so that the tube oscillates at a definite

frequency, but when a synchronizing signal is superimposed on the direct bias the resultant bias is made less negative periodically, and breakdown occurs earlier in synchronism with the signal.

For the observation of transient phenomena on a cathode-ray oscilloscope equipped with a tube having a long persistence screen, a modification of the previous circuit yields a single sweep. As shown in Fig. 6-23(b), the circuit utilizes a thyratron V_1 and a gas diode V_2. The cathode of the diode is con-

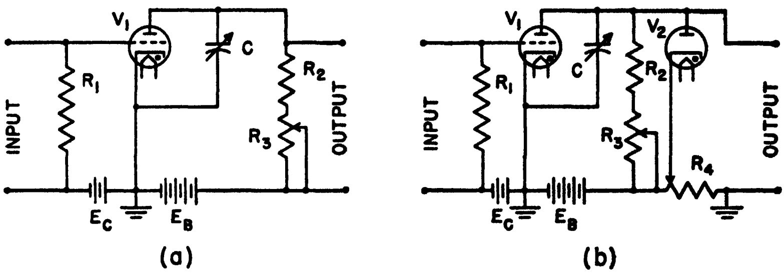


FIG. 6-23. (a) Basic relaxation-oscillator circuit using a thyratron; (b) simplified single-sweep circuit for an oscilloscope.

nected to a potentiometer R_4 by means of which the breakdown voltage of the tube may be regulated so that conduction of the diode takes place at an anode voltage just below that at which the thyratron fires. The diode continues to conduct until a positive signal potential is applied to the grid of the thyratron, permitting this tube to fire at the lower anode voltage. Discharge ceases at the extinction voltage, and capacitor C is recharged through the series resistor R_2. If the signal voltage has been removed in the meantime, the capacitor again charges to the breakdown voltage of the diode and the thyratron does not fire again.

The combination of two thyratrons, one used as a periodically operated single-pole single-throw switch in a pulsing circuit to generate repeated voltage surges, is shown in Fig. 6-24. Thyratron V_1 is of the filamentary type while V_2 is indirectly heated; both receive their cathode heating power from windings on the power transformer T_2. A midtap is used in connection with the filament winding for the tube V_1, whereas no midtap is employed for tube V_2; the equipotential cathode of V_2 is connected

to one side of the filament. The grid-control rectifier V_1 charges capacitor C to a predetermined voltage by the adjustment of the resistor R_1 in the phase-shifting network. A resistor R_2 limits the grid current for tube V_1, and R_3 performs the same function for tube V_2. The autotransformer T_3 is shown with a low-voltage primary winding and a high-voltage secondary winding, although any desired turns ratio may be used, depending on the purpose for which the device is designed.

After the cathodes of the tubes have assumed their operating temperatures, the switch S is closed and capacitor C is charged

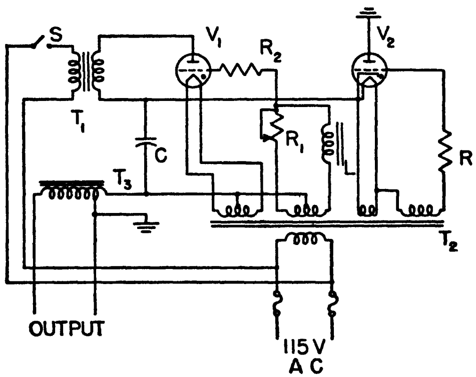


FIG. 6–24. Circuit of a surge or pulse generator.

to a definite voltage through tube V_1 during the positive half-cycle. The lower terminal of C has a positive polarity with respect to the upper terminal. During the charging period, the capacitor cannot discharge through the primary winding of transformer T_3 and through the tube V_2 because the grid of V_2 is supplied from a winding on transformer T_2 with an alternating voltage which is phased so as to be momentarily negative with respect to the cathode. During the next alternation of the power-supply voltage, the anode of tube V_1 is negative and conduction ceases during that half-cycle, but the grid of tube V_2 is positive with respect to its cathode, and the capacitor C discharges through tube V_2 and the primary winding of T_3, resulting in a voltage pulse across the output terminals of the secondary winding. The process occurs once during each cycle of the a-c power supply as long as the switch S remains closed.

Circuits of this kind produce adjustable high-voltage pulses for

test purposes. For instance, transformer T_3 may consist of an automobile ignition coil and the device can then be used for testing spark plugs. In another application, a suitable high-voltage transformer may replace T_3, and the apparatus supplies repeated surges for the testing of insulation in electrical equipment.

6–8. The Excitron

Mercury-arc rectifiers were developed early in this century and achieved prominence during the expansion of street railways, which require direct current for their operation. Electrolytic reduction of aluminum and magnesium, as well as the expansion of other electrochemical processes, made additional d-c demands and added to the popularity of the rectifier. Early rectifiers converted single-phase alternating current to direct current by means of an arc between a mercury-pool cathode and carbon anodes located within a glass envelope. The mercury vaporized, later condensed on the cooler walls of the tube, and returned to the pool located at the base of the tube. The two main anodes for a full-wave rectifier were made of carbon or graphite to prevent mercury amalgamation. Initial ionization was obtained by means of a starting anode which consisted of a mercury column that was vaporized by a current when the tube was tilted. Two additional holding anodes were also used to insure continuity of ionization after the tube had been placed in operation.

Large multianode steel tank units, like the one shown in Fig. 6–25, were subsequently developed for use on polyphase circuits. The common mercury-pool cathode is located at the bottom, and the required number of anodes are suspended from the top. Each anode is surrounded by a perforated graphite shield or grid; this prevents mercury from splashing on the anode and causing it to perform as a cathode with resulting arc-back during the inverse-voltage period. Regulation is obtained by changing the grid potential. In normal rectifier service the arc current, as illustrated in Fig. 6–26(a), is commutated from each anode in turn to the anode of the succeeding phase as the voltage on the latter becomes more positive than the one carrying the arc. Arc-current commutation between two phases is not completed instantly; both anodes carry current simultaneously during a brief overlapping period. The duration of this period depends upon the

inductance of the two transformer phases between which the current is transferred and upon the magnitude of the load current to be commutated. Delayed ignition is accomplished by maintain-

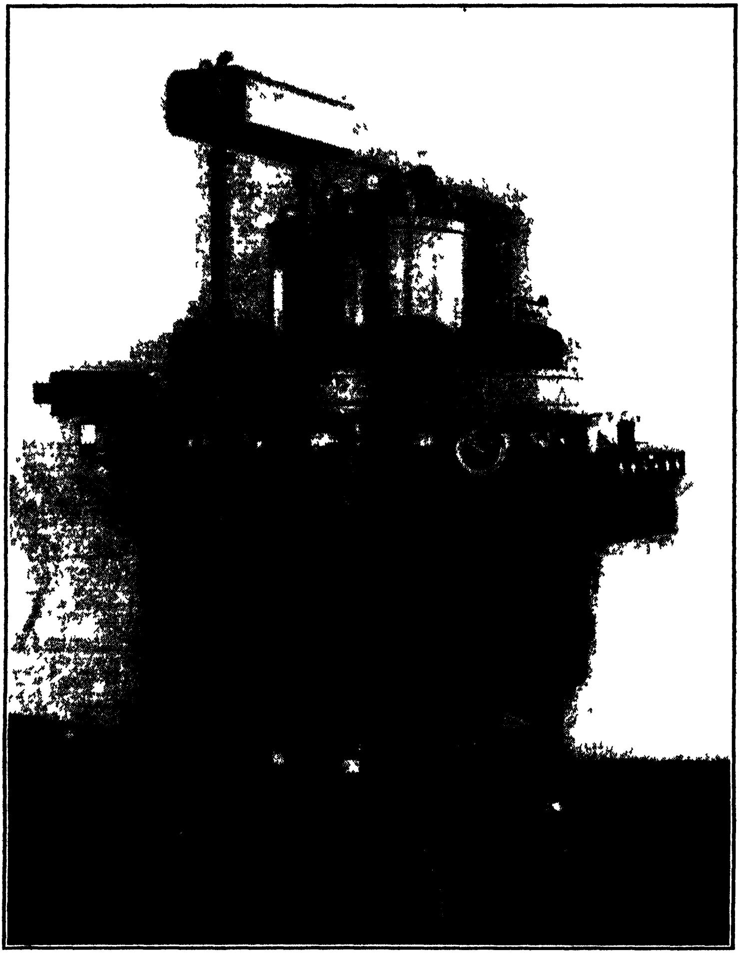


FIG. 6–25. Multianode mercury-arc rectifier. Output rating 500 volts, 3000 amperes direct current. *Courtesy Allis-Chalmers Manufacturing Company.*

ing a negative blocking voltage on each grid in relation to the cathode until the desired firing point is reached, at which instant a positive voltage is applied to "release" the anode. Rectifier operation with grid-control regulation is illustrated in Fig.

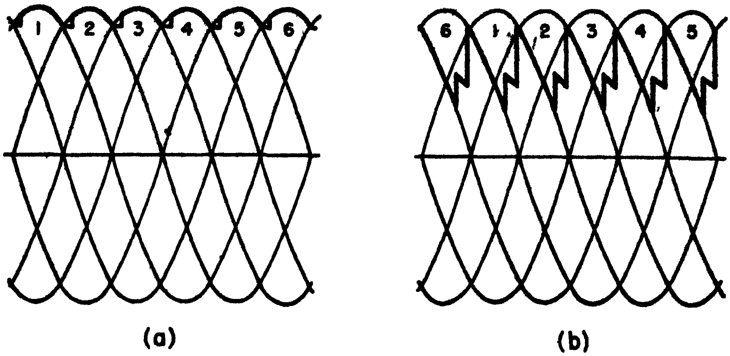


Fig. 6–26. Waveforms of rectified current in a six-phase half-wave mercury-arc rectifier. (*a*) No grid voltage control; (*b*) grid voltage adjusted to reduce average output current.

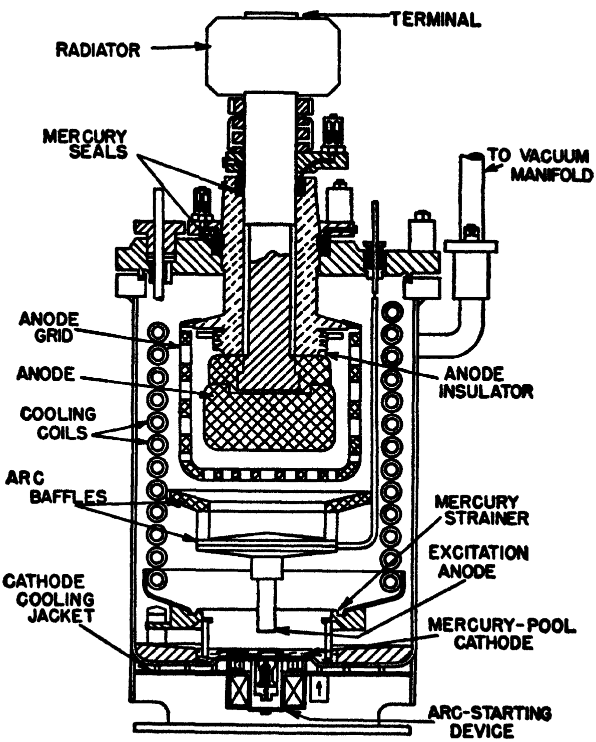


Fig. 6–27. Cross-sectional view of an Excitron-type rectifier. *Courtesy Allis-Chalmers Manufacturing Company.*

6–26(*b*). The power factor of a six-phase rectifier may be as high as 0.95; it is less than unity because of waveform distortion introduced into the a-c system. Regulation by means of grid control causes a decrease in the power factor in proportion to the cosine of the angle of delay, but in any event, the power factor is always lagging.

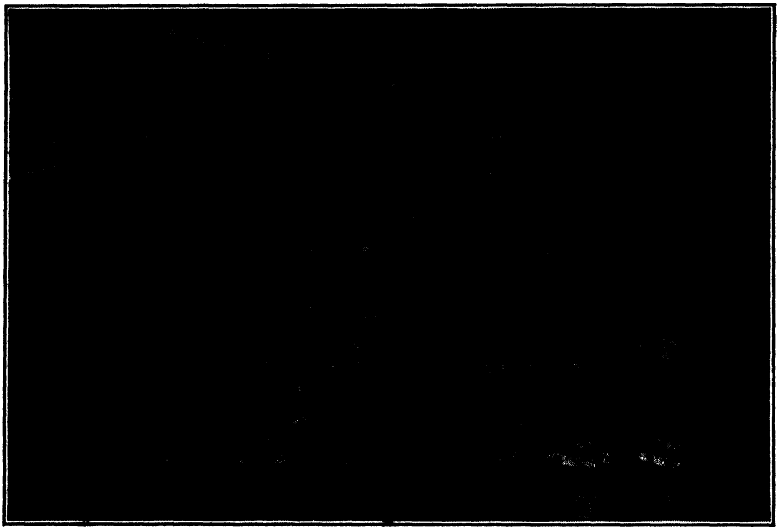


FIG. 6–28. Battery of twenty-four 12-tank Excitron assemblies that supply power to two aluminum reduction circuits. High-speed anode breakers are at the left and cathode breakers are at the right. *Courtesy Allis-Chalmers Manufacturing Company.*

An important improvement in the field of mercury-arc rectification consisted in the development of a single-anode rectifier, which is equipped with auxiliary electrodes for establishing and controlling the arc current. A group of such individual tanks are assembled to produce a polyphase rectifier termed an *Excitron* unit. The advantage of a single unit is that each anode is not exposed to the ionized vapor of the main arc current during its nonfiring inverse-voltage period, as it is in a multianode unit. Therefore, the anode may be located much closer to the mercury pool, resulting in a low voltage drop between the electrodes and a correspondingly improved operating efficiency.

A cross-sectional view of an individual tank is shown in Fig.

6-27. The mercury pool, surrounded by a quartz ring which prevents the cathode spot from traveling up the inside of the tank, is located at the base, and the graphite anode, supported by a steel shaft and suspended from the top of the tank, is mounted above it. A graphite grid surrounds the anode, and an excitation anode, which operates in conjunction with the arc-starting device, is mounted above the mercury pool. Cooling coils allow

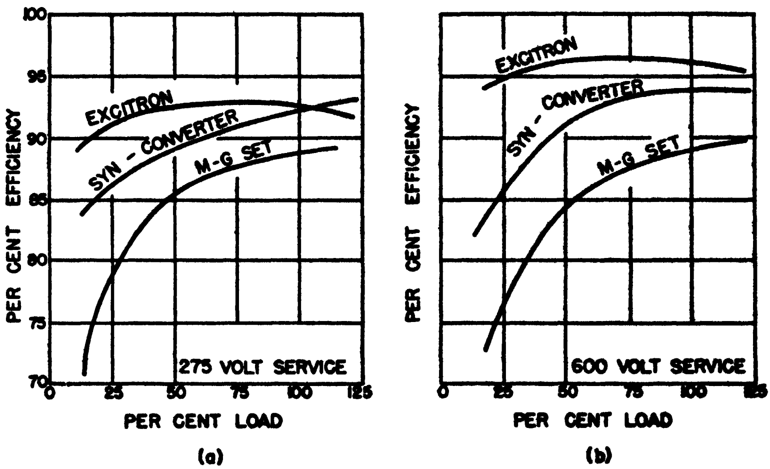


FIG. 6-29 Typical curves illustrating comparative efficiencies of an Excitron rectifier, synchronous converter, and motor-generator set; (*a*) 275-volt service; (*b*) 600-volt service.

water to circulate within the tank, and a fin-type radiator aids in cooling the anode. A vacuum pump removes any air that may leak into the tank and removes occluded gases given off by the electrodes during operation.

The mercury-jet arc-starting device is welded to the bottom of the tank. A plunger with a center hole, located within a steel tube, is caused to move downward against a spring when a surrounding winding is momentarily energized. When the plunger moves, mercury flows through the hole in a solid stream against the excitation anode. A low voltage is impressed between the cathode and the excitation anode, and when the ejected mercury strikes, an arc is established which maintains the cathode spot on the mercury pool. Arc baffles are inserted between the mercury pool and the anode as an additional safeguard against arc-

back. Whenever an Excitron unit is placed in service, each tank must have its excitation established before the rectifier is placed on the line. This is done automatically when a single switch is closed. Means are also provided to restrike any arc if an arc interruption occurs.

A large Excitron installation consisting of 288 individual rectifiers is illustrated in Fig. 6–28. For equivalent ratings, individual units also offer advantages over multianode units as they are smaller in dimensions, much lighter in weight, and can be easily replaced with a spare tank in a portion of the time required for overhauling other types of converting equipment. Typical efficiency curves for an Excitron unit and for rotating converters operating at 275 and 600 volts are shown in Fig. 6–29. It is apparent that the mercury-arc rectifier is very efficient, particularly in traction service where light load factors prevail during long periods of the day.

6–9. The Ignitron

Maximum instantaneous current in a thyratron is limited by electron emission at the cathode; bombardment and destruction of that electrode are inevitable if the rated current is exceeded. The mercury-arc tube, on the other hand, using a mercury-pool cathode, can supply a maximum current limited only by the temperature rise of the tube and the resultant increase in mercury-vapor pressure. It is this ability of the mercury-arc rectifier to supply extremely large momentary overloads without the slightest damage, coupled with its economic advantages, which has made the tube so popular in the steel, mining, transportation, and electrochemical industries.

In 1932 J. Slepian and L. R. Ludwig developed the *ignitron*. This tube eliminates the keep-alive circuit of a mercury-arc tube by the introduction of an ignitor made of a relatively high-resistance refractory material, such as Carborundum or boron carbide. The ignitor is mounted to make contact with the mercury pool, and it strikes an arc at a suitable time while the anode is at a positive potential with respect to the mercury-pool cathode. Connection is usually made to a suitable phase-shifting network, and at the proper time a momentary current flows in the ignitor circuit, producing a small spark at the junction of the ignitor with the mercury surface, establishing the arc, and creating a cathode

spot within a few microseconds. The arc extinguishes at the end of the positive half-cycle, and after a short period the gas deionizes, and the tube remains inoperative, of course, during the succeeding half-cycle.

Ignitrons are manufactured in various forms and may be classified into various types depending on the size and applica-

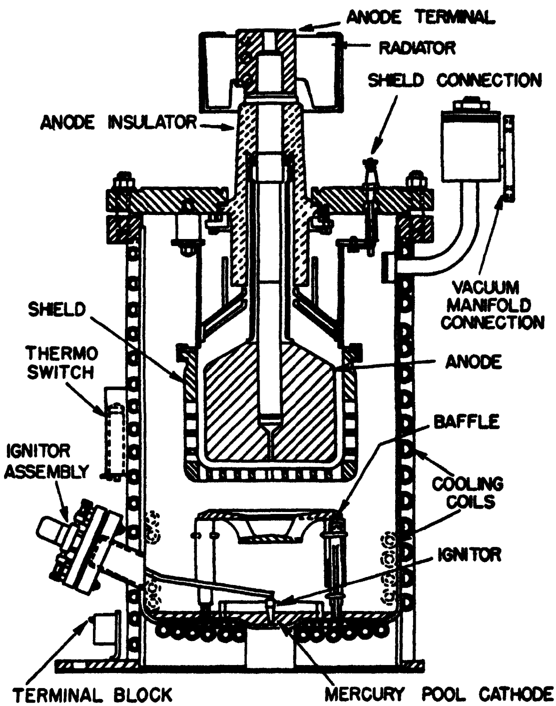


FIG. 6–30. Cross-sectional view of an ignitron. *Courtesy Westinghouse Electric Corporation.*

tion. The permanently sealed tubes are commonly used for the lower capacity installations, which at present range up to 400 amperes in commercial sizes for adaptation in welder circuits and the like, whereas the larger, continuously pumped tubes, like the one shown in cross section in Fig. 6–30, are usually employed in rectification or conversion service and are made in capacities up to 6000 kilowatts for 600-volt installations. A simplified circuit utilizing two ignitrons for full-wave single-phase rectification is

given in Fig. 6–31(*a*); aside from the ignition, to be discussed in the next section, the basic circuit arrangement is similar to that of vacuum-diode rectifiers. An inverse-parallel or back-to-back circuit employing two ignitrons and commonly used in electric welding is shown in Fig. 6–31(*b*). Each ignitron conducts similar to a switch during every other half-cycle, and no direct current but only alternating current flows in the load circuit. A typical ignitron installation, used as a contactor in welding equipment, is illustrated in Fig. 6–32. The two ignitrons are located in the lower compartment, and a group of thyratrons, used in sequence

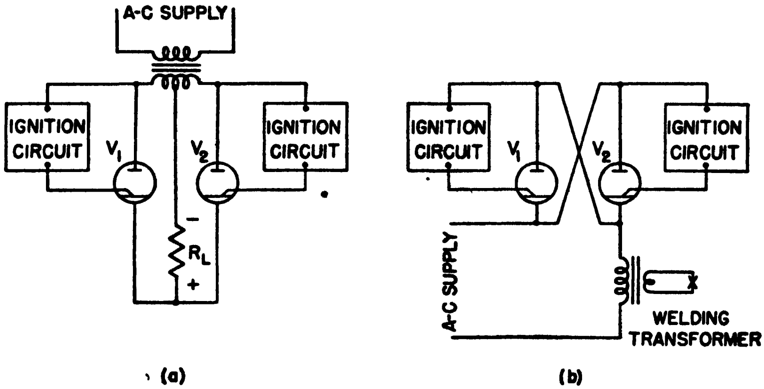
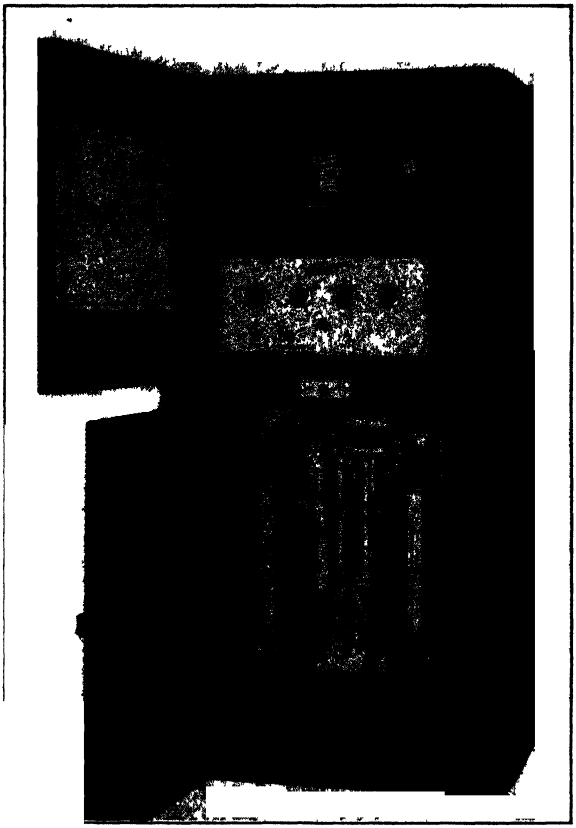


FIG. 6–31. Two ignitrons used in (*a*) full-wave single-phase rectifier circuit; (*b*) inverse-parallel or back-to-back switching circuit.

to time the various operations during welding, are mounted on the back of the upper timer panel.

The rating of ignitrons used in switching service is based on the maximum demand, which consists of the product of the effective current through a pair of tubes, connected back-to-back, and the line voltage, controlled by the tubes. Since the voltage drop across the arc remains essentially constant for various loads, it is apparent from Ohm's law that the internal resistance of the tube varies inversely with the load current, and, therefore, heating varies in direct proportion and not as the square of the load current as in ordinary electrical equipment. The intermittent operation of ignitrons in welder service, where a large current flows for short periods, also needs to be considered in their rating. Practically all ignitrons are water-cooled to dissipate the heat

of the arc and to control the mercury-vapor pressure; they are constructed so that the water flows at a high velocity for efficient heat transfer from the tube walls to the water.



(*a*)

Fig 6–32. Ignitron welding control utilizing two ignitrons as contactors. (*a*) Front of timing control panel has adjustable dials for controlling off, squeeze, hold, and weld intervals, (*b*) thyratrons that control intervals are mounted on rear of panel *Courtesy Weltronic Company.*

Ignitron-rectifier installations, totaling a capacity of more than 3,000,000 kilowatts, have been made during the decade from 1940 to 1950. This undoubtedly represents the greatest application of any electronic device from the standpoint of power utilization. Ignitron rectifiers are preferred over rotating machinery be-

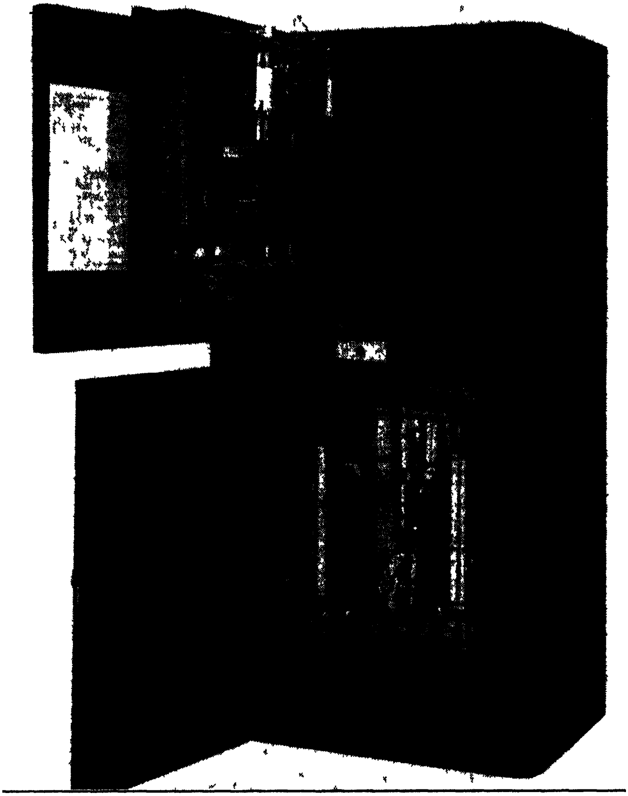


FIG. 6-32 (*b*).

cause of their higher efficiency, lower installation and maintenance costs, absence of noise and vibration, and simplicity of operation.

6-10. Ignitron Excitation Circuits

An ignitron is characterized by the periodic establishment of the arc through the aid of an ignitor whenever the anode of the ignitron is at a positive potential with respect to its cathode. Voltage and current requirements of the ignitor depend on various factors, such as the ignitor material, depth of immersion of the ignitor, and its temperature. In general, ignition will occur if a maximum, instantaneous, positive voltage of about 200 volts is

applied between the ignitor and the cathode, or if a maximum instantaneous current of 40 amperes flows through the ignitor circuit. Ignition time is very short, and the transfer of the discharge to the anode circuit is accomplished within the range of 10 to 100 microseconds; no further demands are then made on the ignitor until the start of the next conduction period, which occurs a complete cycle later. The average current through the ignitor is quite small; however, the large peak current at the desired

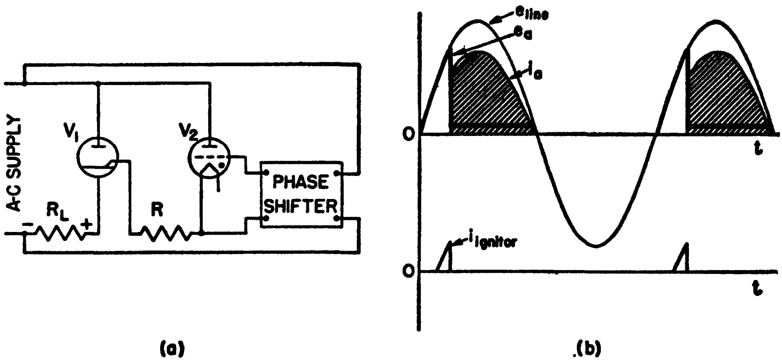


FIG. 6–33. (*a*) Simplified ignitron circuit of the anode-firing type; (*b*) waveforms of applied voltage, voltage across ignitron, ignitron current, and ignitor current.

instant of ignition and the reduction of the ignitor current to zero for the remainder of the cycle require special circuits. Three major ignition circuits have been developed: the anode-firing, the capacitor-thyratron, and the saturable-reactor circuits.

In the anode-firing circuit, shown in Fig. 6–33(*a*), the ignitor receives its energy from the main anode circuit through either a gas-filled diode or preferably through a grid-controlled rectifier, that is, a thyratron V_2, connected in series with the ignitor, the cathode, and the load resistor R_L. Current can flow through the auxiliary tube and cause ignition only when its anode and the ignitron anode are at a positive potential with regard to their respective cathodes. If the tube is a simple rectifier, current begins to flow through the ignitor as soon as the voltage of the positive half-cycle reaches the ionization value of the vapor in the rectifier, that is, about 15 volts. The ignitor fires when the voltage across the ignitor-cathode junction, or the current

through it, reaches the critical value. An instant later, the arc at the junction is transferred to the main anode, which is at a higher potential with respect to the cathode because of the voltage drops across the rectifier and the ignitor junction. The ignitron anode current rises abruptly and, in the case of a resistance load, follows the sinusoidal waveform of the voltage to the end of the half-cycle where ionization of the mercury vapor ceases. Because of the establishment of the arc, the voltage across the anode and the cathode of the ignitron falls immediately to a value of about 12 to 15 volts, and since this is essentially equal to the voltage drop across the auxiliary rectifier, the current through the ignitor falls to zero, as shown in Fig. 6–33 (*b*).

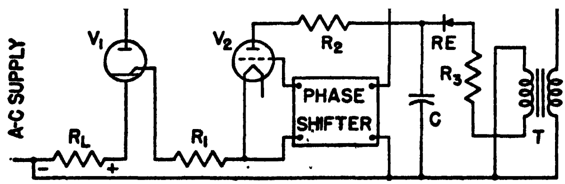


FIG. 6–34. Simplified capacitor-thyratron ignition circuit.

When a thyratron equipped with a phase shifter is substituted for the rectifier, the ignitron may be fired, within limits, at any point along the positive half-cycle, and the average current through the load may be varied continuously from a minimum of nearly zero, obtained by firing the tube near the end of the half-cycle, to the maximum, achieved by firing it near the beginning. The figure shows a single ignitron; for switching service two tubes are used in a back-to-back connection, and for rectifier service the tubes are connected as full-wave rectifiers in single-, three-, or six-phase adaptations. Anode firing, although it has the advantages of simplicity and high efficiency, has certain inherent limitations. For example, the ignitor current flows through the load, and, therefore, if the load resistance is high it may be difficult to obtain ignition.

The capacitor-thyratron ignition circuit, shown in Fig. 6–34, offers greater firing reliability and flexibility than the previous circuit. A capacitor C is charged during one alternation of the supply voltage through a half-wave dry-plate rectifier *RE*. During the succeeding alternation, when the grid of thyratron V_2 reaches the desired firing voltage, as determined by the phase

shifter, the capacitor discharges through the thyratron, the ignitor, mercury pool, and load resistor in series, causing the ignitron to fire. The current pulse through the ignitor results in certain ignition and permits two or more ignitrons to be operated in parallel. This ignition circuit, like the previous one, uses one or more thyratrons, depending on the number of phases of the power circuit and the duty. Thyratrons are rather expensive, and, since their life is not indefinite, tube costs, added

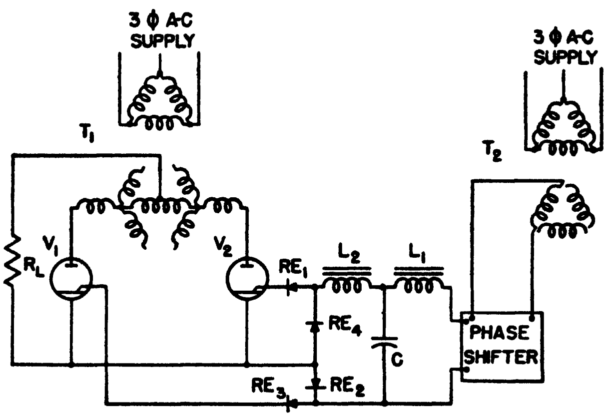


FIG. 6–35. Simplified saturable-reactor ignition circuit.

to the nuisance of unexpected tube failure, makes either of these circuits less popular than the firing circuit to be described next.

The saturable-reactor firing circuit eliminates the thyratron but retains the advantages of initiating the arc by discharging a capacitor through the junction of the ignitor and the mercury pool. Two reactors are shown in the basic circuit of Fig. 6–35; the reactor L_1 is of the conventional kind, consisting of one or more coils wound on a laminated iron core, and is designed to operate on the initial, linear portion, that is, below the knee, of the B–H curve, while reactor L_2 has its winding placed on a core made of a highly permeable material that saturates magnetically when energized with only a few ampere-turns. Capacitor C is charged through the reactor L_1, and a small current, insufficient to cause ignition, flows through the ignitor of V_2 in series with the dry-plate rectifiers RE_1 and RE_2. At a given voltage the reactor L_2 saturates, its impedance becomes very low, and the capacitor discharges as a pulse through the same circuit. Re-

actor L_2 saturates equally well and produces current pulses in either direction, whereas a thyratron conducts only in one. Consequently, as shown in the diagram, one firing circuit is employed to fire alternately two ignitrons at intervals of 180 electrical degrees; three firing circuits can supply the excitation for six ignitrons in a three-phase full-wave rectifier. Grid phase control for each individual firing circuit is obtained from a mechanical phase shifter or more commonly from a phase-shifting network. It will be noted that the particular phase winding of the charging transformer T_2 is different from the phase winding on the rectifier transformer T_1 for which it supplies the excitation. Many combinations of winding connections can be made in three-phase charging transformers so as to produce a suitable phase difference between the capacitor charging circuit and the associated winding on the main rectifier transformer. Such phase displacements, together with a phase shifter, provide a reliable and accurate firing method for an ignitron at any desired phase position while its anode is positive.

6–11. Gaseous-tube Inverters

The process of changing direct current into alternating current is known as inversion, and a tube used for this purpose is termed an *inverter*. Vacuum-tube oscillators perform this function but are used primarily in low-current circuits where sinusoidal waveforms, high frequencies, or a combination of both are required. Mercury-arc tubes and ignitrons, with their low internal resistance, practically constant arc-drop, and large current-carrying capacity, offer the key for simple and highly efficient power inversion. They operate on the basis of alternately switching a unidirectional current from the d-c source through mercury-arc tubes or ignitrons to the two portions of a center-tapped transformer winding. Before considering circuits for gaseous-tube inverters, it may be well to recall some of the characteristics of capacitors and inductors, because inverter operation also depends on the use of these reactive circuit elements.

Time constants of reactors were discussed in Sec. 3–11, and it was also mentioned that, when a constant voltage is suddenly applied to the combination of a capacitor in series with a resistor, the voltage across the capacitor does not rise instantaneously but exponentially. At the instant immediately after the switch is

closed, the circuit acts as if the capacitor were short-circuited, and a current, limited only by the circuit resistance, flows momentarily. Of course, the voltage across the capacitor rises quickly, and the current drops practically to zero within a short period depending on the value of the time constant. When the circuit is subsequently opened the capacitor voltage remains constant except when a resistor is connected across the capacitor, when the voltage decreases exponentially. In an inductive cir-

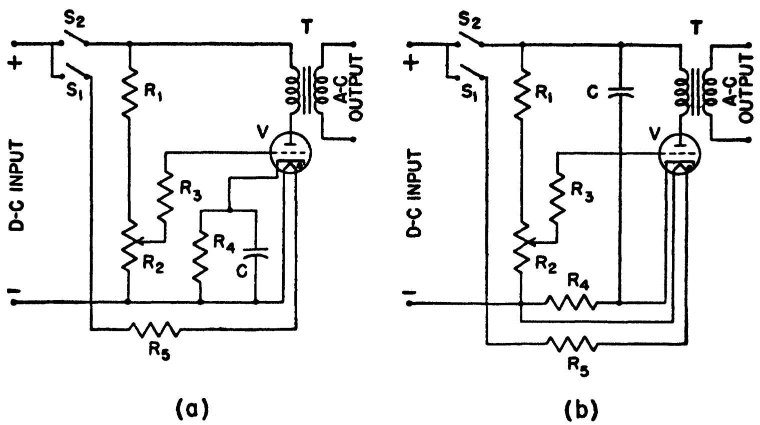


FIG. 6-36. (a) Series-type inverter circuit; (b) parallel-type inverter circuit.

cuit, current cannot rise to its maximum value or fall to zero instantaneously; there is a similar delay, also determined by the time constant. The establishment or decay of the magnetic field surrounding an inductor in which a changing current flows causes the generation of a voltage that is directed against the impressed voltage for an increasing current, or causes the generation of a voltage that is directed with the impressed voltage to prolong the current flow for a decreasing current.

A capacitor is used to interrupt the direct current that flows through a single inverter tube, or to commutate, that is, to switch the current from one to the other, in two-tube inverter circuits. The placement of the capacitor C, as shown in Fig. 6-36, determines and designates the device as either a series- or a parallel-type inverter. In both circuits, employing thyratrons, switch S_1 must be closed first to allow the cathode and the tube to reach their operating temperatures. When the switch S_2 of the series-

type circuit is closed the grid is given a definite positive potential with respect to the negative line, depending on the values of the resistor R_1 and the position of the slider arm on the potentiometer R_2. At the moment of switch closure no charge exists on capacitor C, and the cathode is at the negative line potential. At the proper grid potential the tube conducts, and current flows through the primary winding of transformer T, through the tube, and capacitor C is charged with the upper terminal positive and the lower one negative. The resistor R_4, in parallel with the capacitor, has a relatively high resistance, and, consequently, the capacitor charges quickly so that the voltage across it soon becomes equal to the line voltage less the 10 to 15 volts arc drop. The charging current, however, does not stop at this point. Magnetic leakance of the transformer, that is, the inductive effect of magnetic flux that links one winding but not both, and the reflected inductance of the load cause a voltage to be induced which is in the same direction as the applied voltage, since the current decreases, that charges the capacitor to a potential higher than the line voltage. The tube finally ceases to conduct, but now, owing to the voltage across the capacitor, the anode has a negative potential with respect to the cathode. This prevents the tube from conducting again until the charge on the capacitor has been dissipated through the resistor R_4 and until the sum of the voltages in the grid circuit again becomes equal to the critical value.

When the switch S_2 of the single-tube parallel-type inverter is closed, the grid, as before, is given a definite positive potential with respect to the negative line, but at that moment the capacitor C acts as a short circuit to the tube, preventing it from firing, and the full line voltage appears across the resistor R_4. The capacitor gradually charges through resistor R_4, and the cathode, which was initially at the anode potential due to the uncharged capacitor, soon reaches a negative potential with respect to the grid. The tube fires when this potential becomes equal to the critical value, and the capacitor discharges through the primary winding of the transformer and the tube. As in the previous case, the effect of magnetic leakance of the transformer and reflected inductance of the load causes the flow of current to be continued, and the capacitor becomes charged in a reversed direction, that is, the lower terminal becomes positive with respect

to the upper one. This gives the anode a negative potential with respect to the cathode, and the tube, of course, ceases to conduct. In this circuit, as in the previous one, the anode remains at a negative potential for a sufficiently long period for the tube to deionize and for the grid to resume control. The cycle of operations repeats with the recharging of the capacitor. The critical value of the grid-to-cathode voltage, which determines the firing point, is attained earlier or later depending on the position of the potentiometer slider arm, and, consequently, its position fixes the frequency of the inverter.

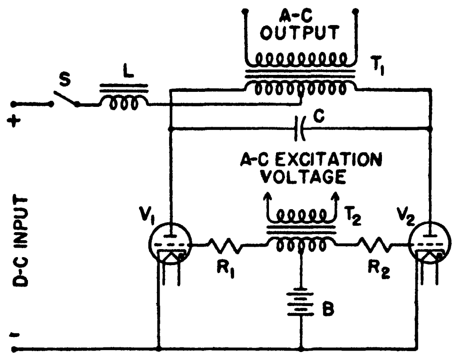


FIG. 6-37. Circuit of a two-tube separately excited parallel-type inverter.

Inverters are either self- or separately excited. The circuit of the separately excited parallel-type inverter, shown in Fig. 6-37, utilizes two thyratrons V_1 and V_2. In a two-tube inverter of this kind, the production of alternating current resolves itself into having each tube conduct alternately at a frequency determined by the excitation voltage that is impressed on the grid circuits by the transformer T_2. The cathode heaters are energized either from the d-c power supply with suitable resistors in series or from the a-c excitation supply. After the cathodes and tubes have reached their operating temperatures, closure of the switch S causes the tube with a momentarily positive grid to fire; it may be assumed that this is tube V_1. Tube V_2 is prevented from firing because of its negative grid potential. The arc drop across tube V_1 is about 15 volts, and nearly all the direct voltage appears across the left-hand portion of the primary winding of the output transformer T_1. During the time the current rises in the left-hand winding, a voltage appears across it of the same polarity

as the voltage induced in the right-hand winding. The sum of these two voltages appears across the capacitor C, which is charged with a positive potential on the right-hand terminal.

Tube V_2 conducts as the excitation voltage reverses, but the negative potential on the grid of tube V_1 is ineffective in stopping the current flow through that tube. However, as soon as tube V_2 conducts, the voltage across it falls to about 15 volts above the negative line potential, the right-hand terminal of capacitor C drops momentarily to the same potential, and, since the voltage across the capacitor cannot change instantly, nearly its full value is impressed on tube V_1 with the anode at a negative potential with respect to the cathode. This, of course, causes the tube to stop conducting; the circuit elements are designed to keep the anode-to-cathode potential at least below 15 volts for a long enough period to allow the tube to deionize and the grid to resume control; otherwise the arc is re-established. In the meantime, the capacitor discharges and immediately recharges in the opposite direction, preparing the circuit to extinguish the arc in tube V_2 as soon as the grid voltage changes and tube V_1 again conducts. The circuit shows an inductor L in series with the center-tapped primary winding of the output transformer. Its inductance, in conjunction with the transformer leakance and the reflected inductance of the load on the transformer, acts to continue the flow of current and to charge the capacitor during any given half-cycle. The grids of the thyratrons are normally biased negatively by means of the battery B.

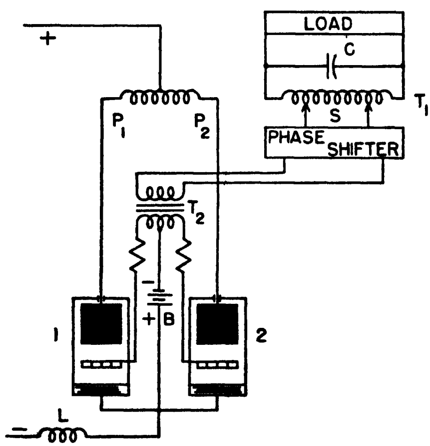


FIG. 6–38. Schematic diagram of a self-excited parallel-type inverter.

Mercury-arc tubes of either the constant-excitation or the ignitron type are used as power inverters. In the schematic diagram, shown in Fig. 6–38, two single-anode mercury-arc tanks are

connected as a self-excited parallel-type inverter. Grid excitation is obtained by feedback from the secondary winding S of the output transformer T_1, which delivers a suitable voltage through a phase shifter to the grid excitation transformer T_2. The commutating capacitor C is connected across the secondary winding of the output transformer; its capacitance is reflected back into the primary circuit and is equivalent to being connected between the two anodes. A load with a leading power factor accomplishes the same purpose, and consequently an inverter when so used requires a small commutating capacitor, whereas a lagging power-factor load needs a large capacitor for proper circuit operation.

Self-excitation can also be applied to the series-type circuit. Although the harmonic content of the a-c waveforms produced by mercury-arc inverters is high, proper circuit and component design yield waveforms that closely approximate sinusoids. Present-day inverters operate at frequencies up to 1500 cycles per second, and for direct voltages of 550 and higher they readily achieve full-load efficiencies of 90 per cent or more.

6–12. Frequency Changers

Mercury-arc tubes or tanks also find application as frequency changers and are used for the transference of electric power between 25- and 60-cycle power systems, for the conversion of 60-cycle to 1000-cycle power for induction heating and melting of metals, and as a source of variable-frequency power for speed control of large a-c motors. Frequency changers are classified into link and composite types: in the link type, individual rectifiers and inverters operate in tandem; in the composite type, each tube performs as a combined rectifier and inverter.

An installation of the link type is illustrated in Fig. 6–39; it shows the external view of a 20,000-kilowatt frequency changer installed as a tie and for transferring power between 25- and 60-cycle systems. Both terminal power circuits are identical, differing only in that the rectifier grids are excited at the input frequency and the inverter grids at the output frequency. The converter is installed in the central housing. The d-c link between the rectifier and the inverter has a length of only a few feet; however, in a somewhat similar installation, power is supplied at 40 cycles and after rectification is transmitted at a high voltage

over a line extending for 17 miles, after which it passes through an inverter and is delivered to a 60-cycle a-c system. Since the maximum and the effective direct voltages are identical, considerably more power can be transmitted over a given line or underground cable with direct than with alternating current because of the requirement of less line insulation, reduction of

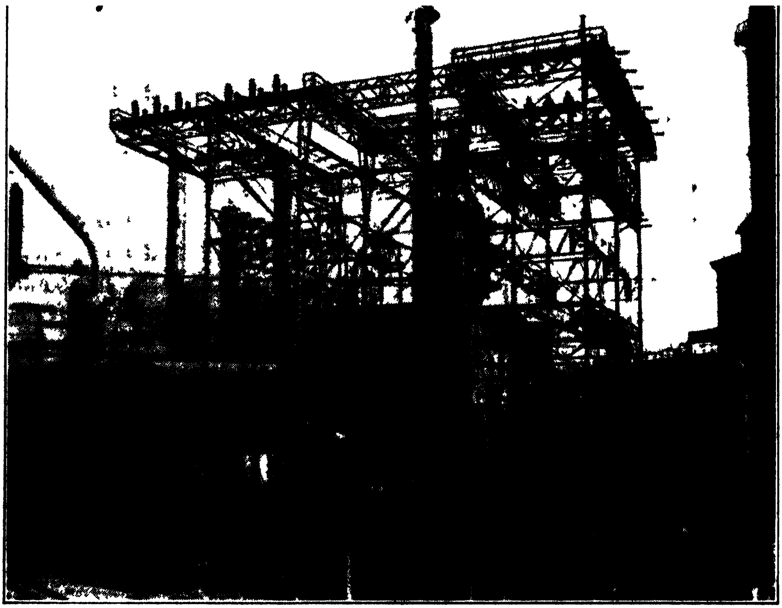


FIG. 6-39. Two 10,000-kilowatt electronic power converters transfer power between a 25-cycle 44-kilovolt system on the right and a 60-cycle 69-kilovolt system on the left. *Courtesy General Electric Company.*

corona loss, and absence of reactance drop. For high tension d-c transmission of power, the frequency at the generator and terminal locations is usually the same, so that the installation may be viewed as a power converter, a general term that includes the frequency changer as a special case. A number of trial installations of various types of electronic power converters have been in operation since 1940; the evaluation of their advantages and limitations requires time and will sooner or later prescribe their specific field of application.

High-voltage conversion systems require specially designed mercury-arc tubes, such as the large pentode ignitron shown in

Fig. 6–40. Discharge is initiated by means of an ignitor every alternate half-cycle, but the cathode spot is also stabilized by means of an auxiliary holding anode. The control grid is located between the shield grid and an intermediate anode, which is

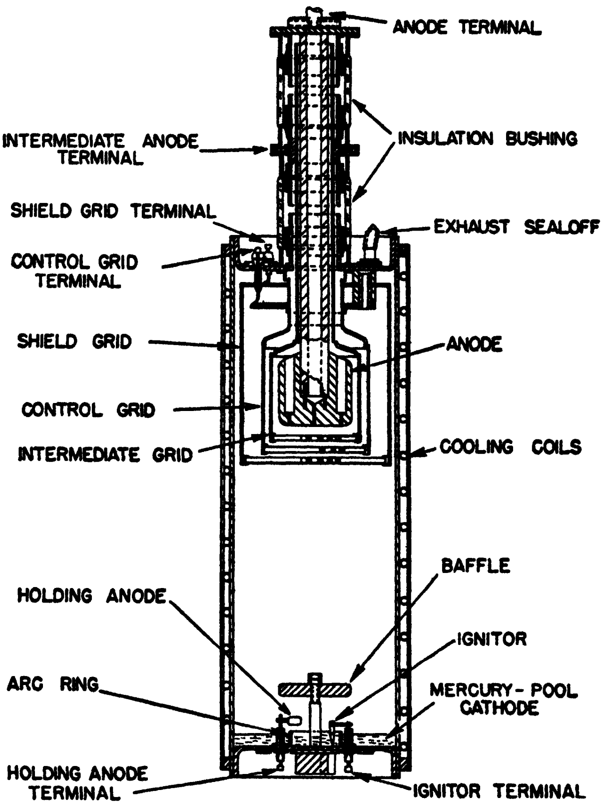


Fig. 6–40. Cross-sectional view of a large pentode ignitron used in high-voltage power conversion. *Courtesy General Electric Company.*

constructed in the form of a grid and serves to divide the potential gradients across the tube during the half-cycles when the anode is negative with respect to the mercury-pool cathode. A positive control-grid voltage is required to fire the ignitron, and this remains constant at approximately 30 volts for a range of d-c anode voltages between 3000 and 20,000 volts. Conduction is first established within the tube by making both the control grid and the shield grid positive with respect to the cathode. The shield

grid aids in establishing ionization and also helps to remove or clean up residual ions at the end of the conduction period. As may be seen from the sectional view, the tube is water-cooled and permanently sealed. This standard ignitron, in either rectification or inversion service, is capable of changing a current up to

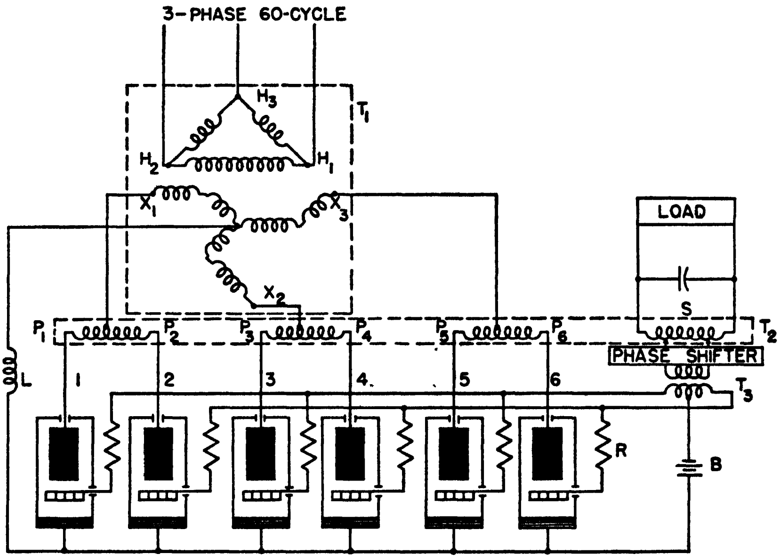


FIG. 6–41. Simplified circuit of a mercury-arc converter for direct conversion of three-phase to single-phase power.

200 amperes at 20,000 volts; that is, it can provide electric power sufficient to serve approximately 15,000 homes.

The simplified circuit of a composite-type frequency changer, used to convert 60-cycle three-phase power to 1000-cycle single-phase power for induction heating, is shown in Fig. 6–41. The tanks numbered 1 to 6 are of the mercury-arc type; the excitation means and its circuit are not shown. A delta three-phase zigzag-connected power transformer T_1 has its primary winding connected to the power-supply line, and its secondary terminals X_1, X_2, and X_3 are connected to three parallel-type capacitor-commutated inverters of the kind shown in Fig. 6–38, but designed to operate at 1000 cycles per second. The cathodes are connected in parallel, and the return circuit is completed through the inductor L to the neutral point on the secondary

winding of the supply transformer. When the converter is connected to the line, each secondary terminal becomes more positive with respect to the neutral point than the other two secondary terminals for 120 electrical degrees, and during that time the corresponding inverter delivers power at a frequency of 1000 cycles per second to the load through the output transformer T_2. For example, during the time when the secondary terminal X_1 is more positive with respect to the neutral point than terminals X_2 and X_3, tubes 1 and 2 are supplied with power through the center-tapped primary winding P_1P_2 of the output transformer and during that time act as an inverter and deliver power to the load. The output may be controlled by adjusting the potential on the grids by means of a phase shifter. After 120 electrical degrees the voltage of terminal X_3 becomes more positive, and the voltage of terminal X_1 approaches zero, with the result that tubes 5 and 6 operate and tubes 1 and 2 are inoperative. During the interval of one cycle, each secondary terminal X_1, X_3, and X_2 will have been more positive in succession with respect to the neutral point during a period of 120 electrical degrees, and, therefore, there is always one pair of tubes operating as an inverter to produce a high-frequency voltage in the secondary winding of the output transformer. With proper circuit and component design, a practically sinusoidal voltage waveform is obtained in the output circuit. The conversion efficiency is about 90 per cent for a 250-kilowatt unit and even higher than this for larger units. Some applications of these highly efficient mercury-arc converters in the field of induction heating for melting, forging, annealing, and deep-surface hardening of large masses will be considered in Chapter 11.

Problems

1. The length of time in seconds required for the potential on the central wire of a Geiger-Müller tube to fall to $1/\epsilon$ of its original value is determined by the time constant RC, where ϵ is the base of the natural logarithms, R is the leakage resistance in ohms, and C is the distributed capacity in farads between the anode and the cathode. How long does it take for the voltage on the tube in Fig. 6–1(*a*) to drop to 60 per cent of its original value?

2. Trace the power-supply circuit of Fig. 6–5 and explain in detail how capacitor C_3 receives its charge.

3. Redraw the multivibrator portion of the circuit of Fig. 6–11, and designate the circuit components as given in that figure, but indicate anode

and grid voltage supplies by batteries. Explain the operation of this circuit in detail.

4. In the vector diagram of the phase shifter shown in Fig. 6–18(*a*), the value of resistors R_1 and R_2 were assumed to be equal. Frequently they are shown in circuits replaced by a tapped potentiometer. In one such instance, the input voltage was 10 volts and the value of R_1 was one-half that of R_2. Draw the vector diagram and plot a curve showing the variation of output voltage with respect to the phase angle ϕ.

5. The induced voltage in the excitation winding of a peaking transformer, energized from a 60-cycle power supply, has a maximum value of 40 volts and occurs within 4.6 milliseconds. It may be assumed that it has a square waveform. The current in the d-c control windings is adjusted so that the induced voltage in the excitation winding fires a thyratron 20 electrical degrees after the beginning of the cycle. Plot the induced voltage versus time relationship to scale throughout two complete cycles.

6. The ionization voltage of a thyratron is 15 volts, the maximum value of the 60-cycle sinusoidal voltage, applied between the anode and the cathode, is 282 volts, and the resistance of the load is 10 ohms. Plot the curve of average current in a full-wave thyratron rectifier operating into a resistance load against a starting angle that varies between 0° and 180°.

7. A gas diode, which requires an anode-to-cathode voltage of 15 volts to maintain conduction, is used to produce an approximate rectangular voltage waveform by clipping the top portion of a 60-cycle sinusoidal voltage beyond a value of 75 volts. Plot the resultant pulses to the same scale for maximum instantaneous voltages of (*a*) 200 volts, and (*b*) 2000 volts.

8. What is your opinion about the relative rating of tubes V_1 and V_2 in the circuit of Fig. 6–24? Why does tube V_1 have a filamentary cathode whereas tube V_2 has an indirectly heated one?

9. Make a list of the unavoidable factors that contribute to a loss in efficiency of (*a*) an Excitron, (*b*) an ignitron, (*c*) a synchronous converter, (*d*) a motor-generator set.

10. Redraw the circuit diagram of the two-tube separately excited parallel-type inverter, Fig. 6–37, and indicate the polarities of the voltage on each electrode and across each circuit component at the instant when tube V_1 conducts maximum current.

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7.

Photosensitive Tubes and Devices

The photoemissive cathode, which emits electrons when illuminated by visible light or invisible radiation, forms the basis for an important group of tubes termed *phototubes.* Aside from their many unique adaptations, these tubes also are applied extensively in measurement, counting, control, and safety devices where they perform as simple and economic substitutes for elaborate mechanical equipment. The tremendous growth of the motion picture industry dates from the time silent pictures became obsolete; now every motion picture projector is equipped with a phototube to translate the sound track on the film into electrical impulses that are amplified and subsequently reproduced. Television, after many years of intensive development work, has emerged from the laboratory with a number of highly specialized phototubes that play an important part as electronic cameras to pick up the scenes to be televised and broadcast. A less spectacular, but nevertheless very important, application of photosensitive devices lies in the field of light measurement to determine proper illumination intensities for home, office, or shop.

7-1. Photoelectric Action and Tube Construction

One of the early discoveries regarding the photoelectric effect was made by R. Hertz, who in 1887 observed that a spark discharged across two electrodes at a lower voltage when the negative electrode was exposed to ultraviolet radiation. A year later W. Hallwachs discovered that a negatively charged plate, which normally retains its charge over a long period, loses that charge quite rapidly when similarly exposed. In 1905 A. Einstein

formulated the basic theory of the photoelectric effect by extending the quantum theory wherein he considered radiation to act as if it were concentrated in bundles or quanta of energy whose magnitude varies directly with the frequency of the radiation. The particle of radiation is termed the *photon*. It has mass but does not possess an electric charge; nevertheless, it has the ability as it moves with the speed of light to exert a force on a neighboring electron. On the basis of this theory the Hallwachs effect is explained by the emission of electrons brought about by photon bombardment.

Each photon, if it has sufficient energy, can dislodge an electron from a photoelectric cathode. Since the number of photons is directly proportional to the intensity of light, we have the basis for the first law of photoelectric emission, which states that the number of electrons emitted from a photoelectric surface per unit time is directly proportional to the intensity of the incident light. There is a second law, readily determined by applying a retarding potential to an adjacent collector electrode, which states that the maximum energy of electrons emitted from a photoelectric surface is independent of the incident light intensity but is directly proportional to its frequency.

If a photoelectric surface is illuminated with a uniformly intense monochromatic light, and if the frequency is changed, the number of emitted electrons also changes. For any specific photoelectric surface these data are determined experimentally, and the results are plotted as a spectral response curve. There is a minimum frequency of light, termed the *threshold frequency*, below which all electron emission ceases; for at that frequency, the energy of each photon has decreased to the point where it is insufficient to remove electrons from the specific photoelectric surface. The threshold wavelength of light for a tungsten surface is about 2300 angstrom units, a value well within the ultraviolet range. This wavelength for a thin cesium film is in the infrared region at about 10,000 angstrom units; and, therefore, such a surface responds to visible light whereas the tungsten surface cannot. These and other facts are derived from Einstein's equation

$$\tfrac{1}{2}mv^2 = hf - e\phi \text{ joules,} \qquad (7\text{–}1)$$

where m and e are the electron constants, v is the velocity of the

emitted electrons, f is the frequency of the impinging monochromatic light, h is Planck's constant, and ϕ is the voltage equivalent of the work function of the photosensitive surface. When the incident light has such a low frequency that the elec-

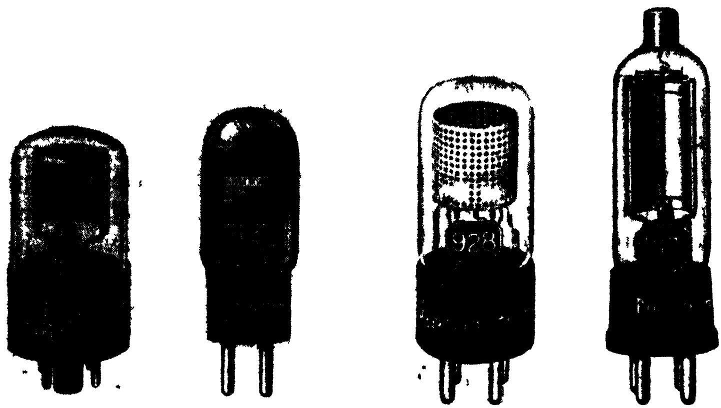


FIG. 7-1. A group of representative phototubes illustrating types of design and showing placement of electrodes. *Courtesy Radio Corporation of America.*

trons emerge with zero velocity, then $v = 0$, and the minimum or threshold frequency f_0 of light that can cause electron emission is

$$f_0 = \frac{e\phi}{h}. \tag{7-2}$$

The equivalent threshold wavelength λ_0 is

$$\lambda_0 = \frac{c}{f_0} = \frac{hc}{e\phi} = \frac{12{,}350}{\phi} \text{ angstrom units,} \tag{7-3}$$

where ϕ is given in volts and c is the velocity of light. (See Eq. 5-4.) A photosensitive surface must have a work function of about 1.5 electron volts or less if it is to respond to visible light within the range of 4000 to 8000 angstrom units. In general, photosensitive films produce greater electron emission than pure metals; however, the base material, the nature of the surface, and its heat treatment are important factors in determining the sensitivity and spectral response.

Phototubes, as shown in Fig. 7-1, are made in a number of types and designs; they consist essentially of two electrodes, a

semicylindrical cathode and an axially located rodlike anode, mounted within a glass envelope. The cathode is made of a silver or nickel base and coated with a light-sensitive surface, such as tungsten, titanium, thorium, or, more commonly, a cesium film deposited over a cesium oxide layer. The anode is designed and located so that it does not appreciably obstruct the passage of light or radiant energy.

The two types of phototubes, the vacuum and gas-filled, are the same in structure, but the one has a high vacuum, whereas the other, after evacuation, is filled with an inert gas at a very low pressure. The presence of gas increases the anode current by the production of ions and by the emission of additional electrons by ionic bombardment of the cathode. Ionization increases rapidly with an increase in anode voltage until a continuous glow discharge occurs. Since the photosensitive surface is destroyed under that action, gas-filled phototubes must always be operated with limited anode voltages and with a series resistor in the anode circuit for additional protection. Tubes of this class have the advantage of greater current output for a given illumination but lack the stability of performance of the vacuum phototube.

7-2. Phototube Characteristics

Before analyzing phototube characteristics and making comparisons between them, it may be well to review certain illumination terms. The unit of light intensity is the international candle, and a light source is rated in terms of a number of *candlepower*. The measure of luminous or radiant flux is the *lumen*, which is the flux incident upon an area of 1 square foot of a sphere's surface that has a radius of 1 foot and is illuminated by a uniform point source of light having an intensity of 1 candlepower located at the center of the sphere. A one-candlepower source of light emits a total flux of 4π lumens. Illumination or flux density is measured in foot-candles, each *foot-candle* being equal to 1 lumen per square foot.

The light intensity on a surface, illuminated by a point source of light, varies inversely as the square of the distance; that is,

$$L = \frac{CA}{D^2}, \tag{7-4}$$

where L is the light flux in lumens, C is the candlepower of the light source, A is the area of the surface in square feet, and D is the distance in feet of the light source from the surface. Although the recently developed concentrated arc lamp, with its incandescent zirconium oxide pellet, produces almost a point source of light, any light may be considered a point source if its dimensions are negligible in comparison with the distance from which it is observed. Phototubes are generally used with

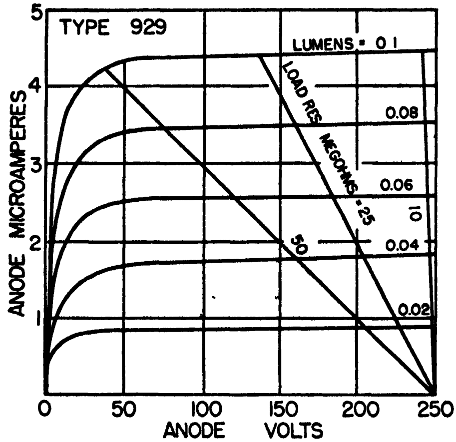


Fig. 7–2. Anode characteristics and anode diagram for a typical vacuum phototube.

tungsten-filament light sources operating at a temperature of 2870° K. The maximum radiation from such a source occurs at about 10,000 angstrom units with only about 5 per cent of the relative energy radiated at 4000 angstrom units; this makes its use highly acceptable for application in the red and infrared regions but practically prevents its utilization in the blue and violet portions of the visible-light spectrum.

Anode characteristics of a phototube are obtained by connecting a variable source of direct voltage, a variable resistor, and a microammeter in series between the cathode and anode terminals with the voltage supply connected to make the anode positive with respect to the cathode. A family of these characteristics for various light flux values of a typical vacuum phototube are shown in Fig. 7–2.

Maximum output current of a phototube consists of only a

few microamperes; it depends on the luminous flux which for most tubes has a maximum rating of only a fractional part of a lumen. The *luminous sensitivity* of a phototube is expressed as the current in microamperes per lumen of light flux. Measurements are usually made at 0.1 or 0.5 lumen, and for vacuum-type tubes the sensitivity ranges between 15 and 35. The diagram also shows three load lines, constructed to pass through a point on the anode-voltage axis corresponding to the supply voltage, and through a point on the anode-current axis obtained by dividing the anode-supply voltage by the load resistance. Characteristic curves in the diagram are plotted for equal increments of light flux, and, since they are practically straight equidistant lines beyond saturation, they cross the load lines at equidistant points. The anode current and the voltage across the load resistor for a vacuum phototube operated at a high anode voltage are for all practical purposes directly proportional to the luminous flux. It is also evident that high values of supply voltage and load resistance must be used in the anode circuit if substantial output voltages are to be obtained from the relatively minute anode-current changes.

Although any one of the inert gases may be used, a good compromise for a gas-filled phototube is obtained by evacuating the tube and introducing argon at about 0.1 millimeter of mercury pressure. Average anode characteristics of a typical tube are given in Fig. 7–3. The curves are essentially similar to those of a vacuum-type phototube for low anode voltages but deviate by rising rapidly when the voltage exceeds about 15 volts. Deviation of the curves from straight lines is caused by the progressively increasing ionization of the gas, which increases the sensitivity to 125 microamperes per lumen or more. Gas-filled phototubes, however, are seldom operated at anode supply voltages in excess of 90 volts in order to prevent a glow discharge. The characteristics are not straight, equidistant lines, and, consequently, the anode current and output voltage are not directly proportional to the flux. A reasonably linear relationship may be achieved by means of a sufficiently high anode resistance, a low anode voltage, or a combination of both.

Phototubes differ in their spectral sensitivity, that is, in their response to light of different wavelengths, according to the nature and construction of the photosensitive cathode. In general, the

metallic films, such as those of tungsten or titanium, sputtered on solid or plated base metal, yield a response with a single maximum extending over a rather narrow range of wavelengths, whereas cathodes made by the deposition of an alkali metal, such as lithium, potassium, sodium, or particularly, cesium with a layer of cesium oxide between it and the base material, frequently have an irregular spectral response with several maxima and minima. The threshold wavelength limits the response at

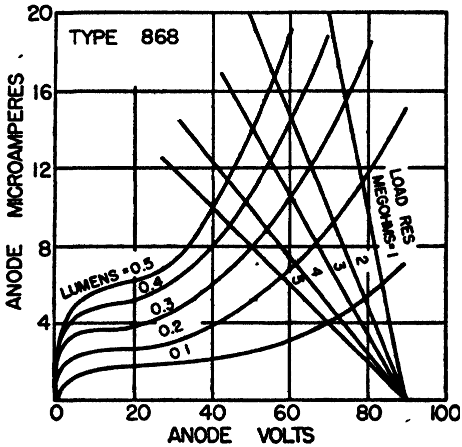


FIG. 7–3. Anode characteristics and anode diagram for a typical gas-filled phototube.

one end of the spectrum, and the transmission characteristics of the glass envelope cause the response to terminate at the other. Of four standard photosurfaces, the color sensitivities of those shown in Figs. 7–4(*a*) and (*b*), and termed *S*–1 and *S*–2 photosurfaces respectively, are suitable for energization by light predominantly red in color or for operation with infrared radiation. The *S*–3 photosurface, Fig. 7–5(*a*), has a spectral sensitivity that extends throughout the visible spectrum with a maximum response in the blue portion. The relative response of such a tube to light reflected from colored objects approximates that of the eye more closely than that of other photosurfaces, and this tube is therefore commonly used in circuits for colorimetric determinations. The *S*–4 photosurface response, shown in Fig. 7–5(*b*), has a very high sensitivity in the blue-violet region and is particularly adapted for operation with day-

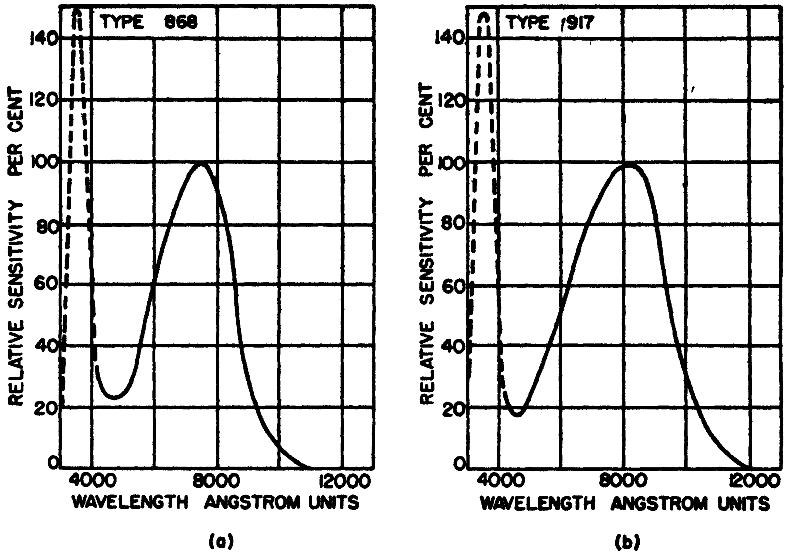


FIG. 7-4. Spectral sensitivity characteristics of phototubes equipped with (*a*) *S*-1 photosensitive surface, and (*b*) *S*-2 photosensitive surface.

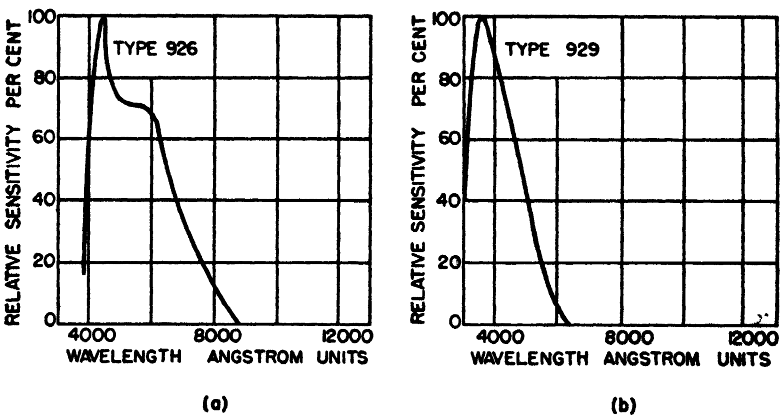


FIG. 7-5. Spectral sensitivity characteristics of phototubes equipped with (*a*) *S*-3 photosensitive surface, and (*b*) *S*-4 photosensitive surface.

light or with light from a carbon-arc or mercury-vapor lamp. Although this surface has low red sensitivity, it gives excellent response compared with the other surfaces when illuminated by light from an incandescent lamp operated at 2870° K because

of the fact that the inherent sensitivity, on an energy basis, of a tube employing this surface is ten or more times that of a conventional red-sensitive phototube. It will also be noted that the S–4 surface does not respond to infrared radiation, a distinct advantage for flame-control applications.

Frequency response for a vacuum phototube obtained with modulated light is essentially constant up to about 20,000 cycles per second. Capacitance between the electrodes and between the leads has a value of at least several micromicrofarads and limits the response to higher frequencies. The output of gas-filled tubes, on the other hand, decreases as the frequency is increased. Positive ions have a much lower velocity than electrons, and a definite time interval exists between the instant an ion is formed and the moment at which it strikes the cathode. Illumination of the cathode, therefore, produces a primary photoelectric current followed slightly later by the positive-ion current. The net effect of this is to smooth out or to decrease the varying component of the phototube current and to decrease the sensitivity, which is about 17 per cent less at 10,000 cycles per second than at 100 cycles per second. This is important in sound reproduction of motion pictures where highly sensitive gas-filled cesium oxide phototubes are used; however, compensation is made in such applications by employing an amplifier that has a rising amplitude versus frequency characteristic.

7–3. Basic Phototube Circuits

The small output current variations of a phototube are insufficient to operate a relay directly or to effect control operations; it is necessary to employ a vacuum tube or a thyratron to amplify the current variations as they manifest themselves in the form of a voltage drop across the load resistor.

A simple phototube and amplifier circuit is shown in Fig. 7–6(a). The amplifier tube V is battery-operated, and a relay RY is connected in the output circuit. The phototube circuit consists of the phototube PT, the anode power supply B_4, and the load resistor R_1; it is coupled to the amplifier by means of resistor R_1. With no illumination, no photoelectric current flows through resistor R_1, and the grid of the amplifier tube, being biased through R_1 to a voltage determined by battery B_3, permits an anode current which is insufficient to energize the relay

to flow through tube V. When light strikes the phototube, a current flows through resistor R_1, and a voltage drop IR, that makes the upper terminal of the resistor positive with respect to the lower terminal, appears across it. This is in accordance with Kirchhoff's voltage law, which states that the algebraic sum of the voltages around any closed circuit is equal to zero. The grid circuit of the amplifier tube now contains the steady bias and an opposing voltage, the magnitude of which may be determined from the anode characteristics of the specific phototube. In the typical diagram, Fig. 7–2, the voltage at the point

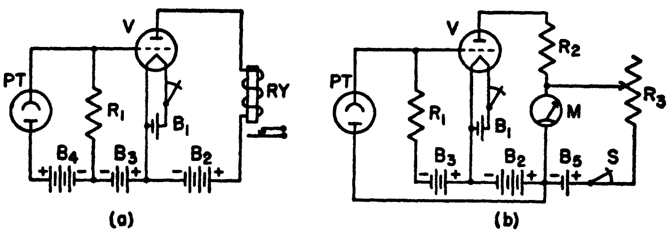


FIG. 7–6. (*a*) Circuit of a phototube coupled to a class A amplifier; (*b*) circuit of a simple illumination meter equipped with an anode-current bucking circuit.

of intersection of the load line with the curve giving the light level indicates the voltage drop across the tube, and the difference between that value and the anode supply voltage is the voltage drop across the load resistor. The resultant grid bias is less negative than before, the anode current increases, and the relay is energized. With a subsequent removal of the illumination, the current through the phototube again returns to zero, the anode current of the amplifier returns to its original value, and the relay releases.

The anode current of a class A amplifier in a circuit, such as the one above, varies in direct proportion as the light striking the phototube increases and decreases. A modification of this circuit, shown in Fig. 7–6(*b*), can be used to measure illumination. Since the anode voltage required by a phototube and that required by an amplifier tube are of about the same order, the phototube circuit can be arranged to obtain its anode supply from batteries B_2 and B_3 in series. Resistor R_2 is connected as a load in the anode circuit of the amplifier. The indicating meter utilizes an additional battery B_5, in conjunction with a

variable resistor R_3, in a *bucking circuit* to reduce the meter indication to zero for the normal anode current of the amplifier. When the phototube is energized, the current through the meter increases in proportion to the illumination. Calibration is ordinarily made in foot-candles. Switch S must remain open when the instrument is not in use; otherwise, the meter indicates in a reverse direction.

Phototubes are rapid in their action, and many circuits are designed to operate from an a-c supply line without the use of

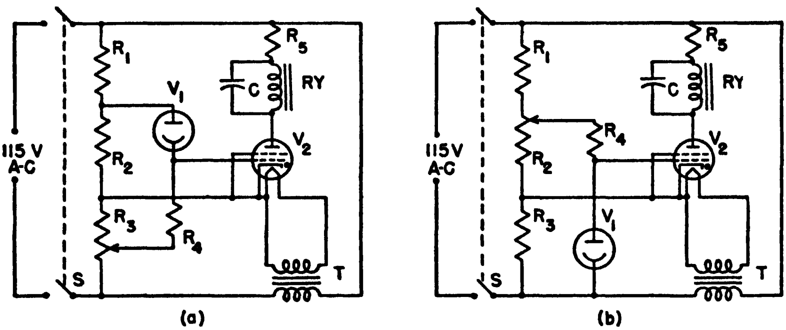


FIG. 7-7. A-c-operated phototube relay circuits. (*a*) Relay energizes with an increase in illumination; (*b*) relay energizes with a decrease in illumination. *Courtesy Radio Corporation of America.*

batteries or a rectifier. It is frequently desirable to employ a larger control current than is normally available from a vacuum tube and to increase the current through the relay abruptly at a given value of illumination; these requirements are met by a thyratron control circuit. A simple a-c-operated circuit, incorporating a thyratron and in which a relay is energized by an increase in light on a phototube, is shown in Fig. 7-7(*a*). The phototube and the thyratron anodes are simultaneously positively charged with regard to their respective cathodes every alternate half-cycle of the line voltage, and current can pass through these tubes only during that time; when the upper switch blade is negative with respect to the lower, both tubes are inoperative. A negative grid voltage is supplied to the thyratron V_2 by the voltage drop across that portion of resistor R_3 located between its slider arm and the junction of R_2 and R_3, which is connected to the cathode. The slider arm is adjusted to make the grid sufficiently negative to prevent the tube from firing when the

illumination on the phototube V_1 is below a critical value. As in the previous circuits, a voltage drop which varies with the illumination exists across resistor R_4 with its upper terminal positive. As the illumination on the phototube rises above the critical value, the resultant voltage drop across the upper portion of R_3 and R_4 in series reduces the grid bias to the point where the thyratron conducts and the relay RY energizes. The capacitor C prevents the relay from chattering, and resistor R_5 limits the current through the relay.

The circuit just described is modified, as shown in Fig. 7–7(b), for reverse operation, by connecting the phototube so that, when the current through it decreases with less illumination, the voltage drop across the load resistor R_4 also decreases and makes the grid less negative, causing the thyratron to conduct. The phototube in either of the circuits of Fig. 7–7 conducts only during alternate half-cycles of the a-c power supply and is subject to irregular operation for light changes having a duration of $\frac{1}{60}$ second or less; d-c power supplies are used when it is necessary to overcome this limitation.

Illumination comparisons by either transmission or reflection can be made by means of two phototubes in a balanced bridge-type circuit. The circuit, shown in Fig. 7–8, is arranged so that an increase in illumination striking one or the other of the phototubes causes a corresponding change in the indication of the meter M. Circuits of this type can be made very sensitive to unbalance; however, ageing of the tubes and other factors require the circuit to be recalibrated periodically. Innumerable circuits utilize phototubes in various forms of process control; they range in complexity from simple devices, such as counters and simple switches, to elaborate adaptations that exercise continuous control in the manufacture of a product.

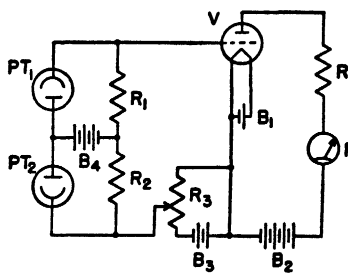


FIG. 7–8. Balanced bridge-type circuit for comparing illumination on two phototubes.

Extremely quick-acting photoelectric relays or control circuits require a d-c source of power supply; for reliability of operation they should respond only to sudden impulses and not to a

gradual change in light, such as may be caused by dust accumulation or by the weakening of the light source with time. The desired action may be obtained, as shown in Fig. 7–9(*a*), by modifying earlier-described circuits by the addition of a coupling capacitor C_1 and the resistor R_3. The phototube is resistance-capacitance-coupled to the amplifier, causing it to respond only to a rapidly varying or alternating signal. With a constant illumination on the phototube, the voltage drop across the load resistor R_2 is also impressed across the capacitor C_1. Gradual

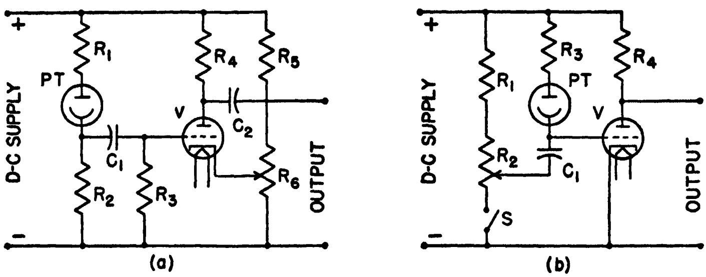


FIG. 7–9. (*a*) Rapid-acting photoelectric control circuit; (*b*) photoelectric circuit for measuring the product of light intensity and its duration.

change of light intensity causes a corresponding slowly changing potential across C_1, and the slowly changing charging current produces no appreciable voltage drop across R_3. A sudden decrease in light intensity, however, produces a sudden drop in the phototube current, and, since the capacitor C_1 cannot change its charge instantly, the difference in the voltage drop across R_2 between the original and subsequent value is suddenly impressed across resistor R_3 and sends an impulse through the amplifier. The circuit responds with high fidelity to audio frequencies. For sound-reproducing applications, the output circuit is connected to additional amplifier stages terminating in loud-speaker equipment; for control purposes, it is connected to one or more thyratrons that operate magnetic contactors or control motor direction and speed.

The basic circuit of Fig. 7–9(*b*) is representative of the type that measures the product of the direct or reflected light intensity on the phototube and its duration. Its principle of operation depends on charging a capacitor C_1 to a voltage equal to the line voltage, with the switch S open, through resistors R_1 and R_2

and the grid-to-cathode circuit. After the capacitor is charged, the switch is closed, and the current through the phototube reduces the charge to the point where the grid potential permits the anode current through tube V to reach a value sufficiently high to either energize a relay in its anode circuit or to supply the trigger voltage to fire a thyratron. The time required to charge the capacitor is only a fractional part of a second, and for a constant light source various values of C_1 may be switched into the circuit to produce an adjustable time-delay relay or timer. By operating the switch with the relay and using a suitable counter, the total illumination which falls on a phototube over an interval of time may be determined.

7-4. Temperature Control and Light Curtain

Fabrication of the millions of piece parts and their assembly has offered innumerable problems in American industry, and production engineers are quick to adopt and utilize any reliable device that speeds production, turns out a more uniform product, or adds to the safety of the operator. The phototube was early recognized as offering important advantages in production processes; it continues to contribute in no small measure to the industrial record of this country. Because of space limitations only a few representative applications will be analyzed in this and in succeeding sections.

A typical phototube installation on production equipment is illustrated in Fig. 7-10. In the assembly of automotive spark plugs, the ceramic insulator is located within the shell with a copper gasket at the top and bottom of a shoulder on the insulator. After an initial centering operation, the metal at the top portion of the shell is cold crimped over the ceramic shoulder in the first press position to the right. The assembly is then transferred to the left position where, on the next operation of the press, pressure is again applied together with an electric current from the secondary winding of a welding transformer between the top and bottom portions of the shell, resulting in hot crimping, that is, deformation of a thin-walled section of the shell to provide a gastight assembly. During the operation the temperature must be controlled accurately; otherwise the metal may become either too hot, resulting in a weak assembly, or not hot enough, resulting in an assembly that is not gastight.

Applying the current for a uniform time interval, or for a given number of cycles, cannot well be used in this case because manufacturing tolerances, for an economic design of the shell, permit large deviations in the dimensions of the thin-walled section. For instance, a tolerance of plus or minus 0.005 inch in a dimension of 1 inch represents a variation of 0.5 per cent, whereas

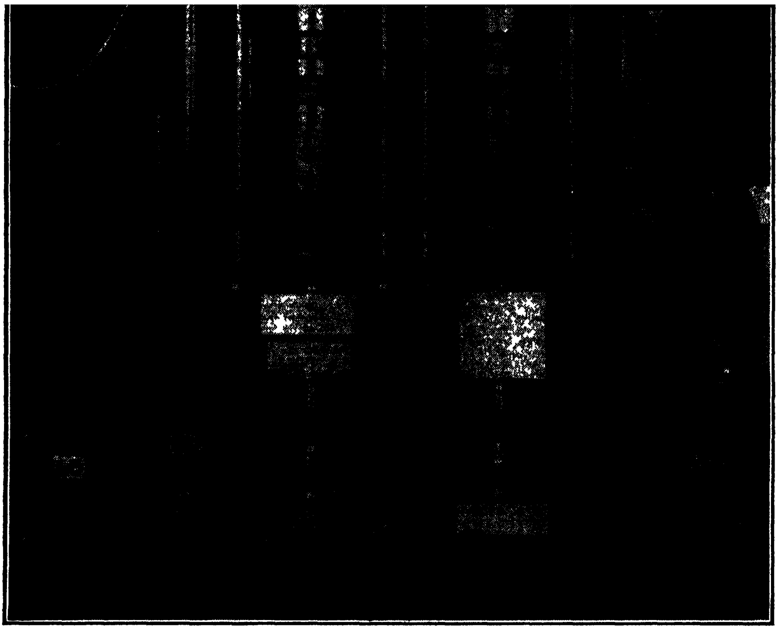


FIG. 7-10. Hydraulic press incorporating temperature control and a light curtain. *Courtesy Agnew Electric Company.*

the same deviation in a dimension of 0.032 inch means a variance of nearly 16 per cent. A phototube is mounted within a telescopic sighting instrument, indicated in the figure as *TC*, and forms the actuating device for an amplifier-operated relay to disconnect the current at a predetermined temperature of the thin-walled section.

A simplified circuit of the temperature control is given in Fig. 7-11. Phototube *PT* is connected in a conventional manner, and a voltage-regulator tube V_3 maintains a constant voltage supply. The amplifier, consisting of tubes V_1 and V_2, is of the direct-coupled type; rectifier tube V_4 supplies the direct voltages. In

order to obtain stabilized voltages and to prevent the operating characteristics of the amplifier from drifting, two auxiliary tubes V_5 and V_6 are used. When the press comes down during a hot-crimp operation, pressure is applied to the shell by means of the two electrodes and the current to heat the thin-walled section of the shell is automatically connected. The temperature rises quickly to the predetermined value at which the crimping operation is effected by increased pressure on the ram, and simul-

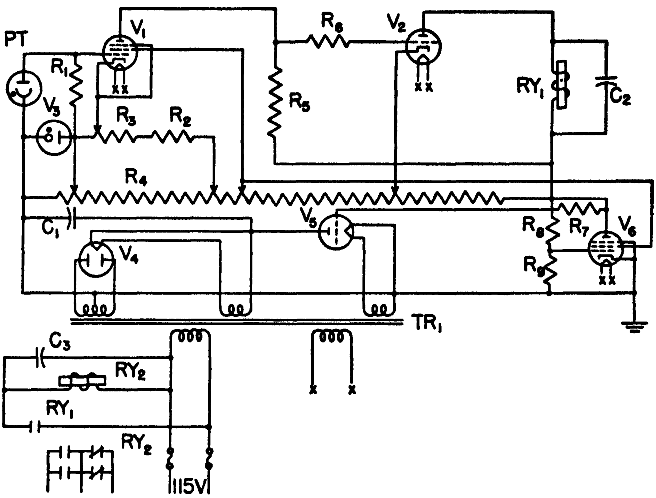


FIG. 7-11. Simplified phototube circuit of the temperature control.

taneously the red and infrared radiation causes operation of the phototube, amplifier, and relay RY_1. Closure of the relay contacts energizes relay RY_2, which is connected across the supply line, and its contacts disconnect the heating circuit. The relays are closely margined; that is, they energize and release within narrow tolerances of current for uniform operation and are of the quick-acting type. For extremely short time intervals, it is, of course, necessary to control the heating current more definitely; this can be done by changing the grid bias on thyratrons that supply the ignition circuits for switching ignitrons.

A second phototube application in this installation is marked *LC*. It consists of a light curtain or safety device to prevent operator injury by stopping downward movement of the press rams and returning them to the normal, wide-open position if

the operator obstructs the light beam across the front of the press. Vertically arranged lamps located at the right within a metal box illuminate through a slot the cathodes of two phototubes, mounted within a similar container at the left of the press. It is an axiomatic production principle that, if power supply failure occurs, particularly in safety devices, the machine remains inoperative and in a nonhazardous position. The nature of the

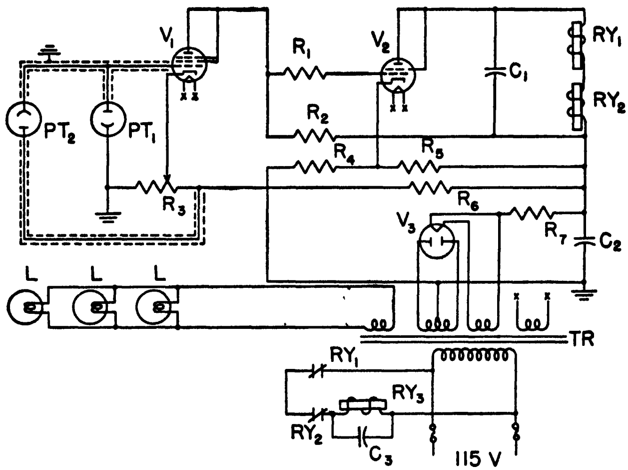


FIG. 7-12. Circuit for the phototube-controlled light curtain. *Courtesy Electronic Control Corporation.*

application also demands that the device be extremely sensitive in its action so that, for example, if the operator only introduced a finger to attempt readjustment or removal of the piece part the light would be intercepted sufficiently to cause the phototube to operate.

In the circuit of the light curtain, shown in Fig. 7-12, the two phototubes PT_1 and PT_2 are connected in series. An arrangement of this type is commonly used to determine photometric qualities and finds application in the precise measurement of color or luminous intensity by exposing one of the phototubes to the standard and the other to the unknown. If one of the phototubes, for example PT_2, is irradiated with an unvarying source of light it may be considered to be the load resistor for PT_1, and any change in the illumination on PT_1 will change the grid voltage on amplifier tube V_1. The diagram of Fig. 7-13

illustrates the action of the input circuit. Both phototubes are considered to be identical, and the figure shows the current-voltage characteristics of PT_1 and PT_2, the latter being drawn as the load line for PT_1, since the two tubes are in series and the same current flows through both. The point of intersection of the two curves gives the magnitude of voltage across PT_1, and the difference between this voltage and that of the anode

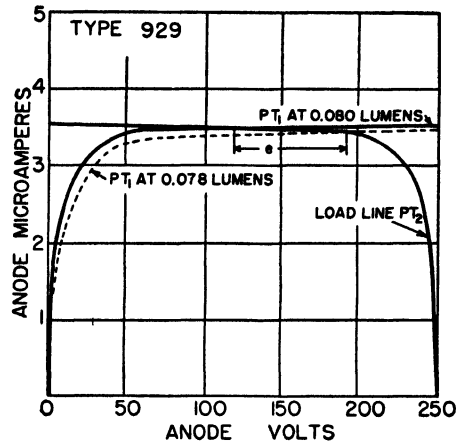


FIG. 7-13. Anode characteristics of the phototubes in the light-curtain circuit, showing one characteristic drawn as the load line for the other.

supply is the voltage across PT_2. The normal operating point is selected to fall on the upper flat portion of the curve.

When the illumination on PT_1 decreases, the characteristic curve also changes; the reduced illumination curve is shown in the figure as a dashed line. The point of intersection of the two curves has now been moved to the right, and the difference of potential e between this voltage and the previous one is impressed on the grid of the amplifier tube. This phototube circuit not only produces rapid response to extremely slight variations of intensity of the light beam, but it also has the advantage that variation of light on either tube produces response. Two relays RY_1 and RY_2 are connected in series in the output circuit of the amplifier tube V_2. Each relay is equipped with make-and-break contacts and is connected so that either energizing one or releasing the other opens the current supply to relay RY_3, which immediately relieves the hydraulic pressure on the ram of the

press and causes it to assume its normal inoperative position. The press cannot be operated as long as relay RY_3 remains released, and it continues inoperative until the relay again becomes energized.

7–5. Measurement and Inspection Equipment

Phototubes play an important part in measurements and in inspection tests wherever visual indications form the foundation;

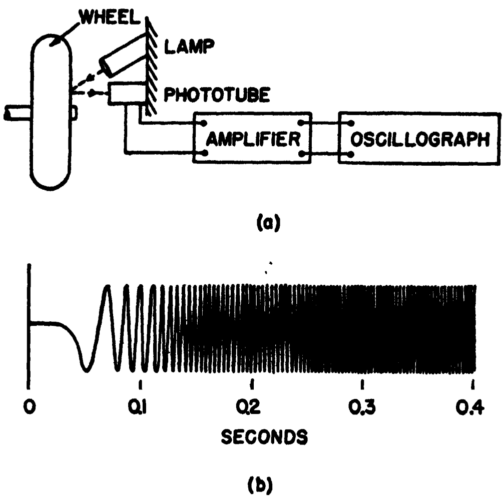


FIG. 7–14. (*a*) Schematic diagram of a device for the determination of angular acceleration and velocity of an airplane wheel during landing; (*b*) tracing of a typical oscillogram. *Courtesy United States Army Air Forces.*

this includes nearly every measurable quantity. For instance, aeronautical engineers are interested in determining the angular acceleration and velocity of the wheel on an airplane landing gear from the moment it touches the ground until it reaches its maximum speed. Tests of this kind are made in conjunction with strain measurements to determine drag loads in landing gear structures and yield invaluable data for purposes of analysis and design. The instrument, known as a photoelectric tachometer and shown in Fig. 7–14(*a*), consists of a phototube operating into an amplifier, which actuates a recording oscillograph. Input signals to the phototube are obtained by the reflection of light from uniformly spaced white marks painted radially on the tire. An

oscillogram, such as the tracing of one shown in Fig. 7–14(*b*), indicates angular positions of the wheel from which angular velocity and acceleration may be calculated.

Scale manufacturers have improved the accuracy and speed of automatic weighing by employing the frictionless and accurate light beam with phototube equipment. In one form the material to be weighed flows rapidly into the scale pan until the pointer begins to intercept the light beam and causes the photoelectrically operated relay to reduce the rate of flow of the material to a



FIG. 7–15. Photoelectric pinhole detector for tin plate. *Courtesy Westinghouse Electric Corporation.*

very low value. At the exact weight the pointer completely interrupts the light beam, with subsequent flow stoppage.

Photoelectric relay equipment has reached a high state of perfection in mechanical inspection apparatus. The pinhole detector, used in the fabrication of tin plate and illustrated in Fig. 7–15, consists of a light source, a group of phototubes connected in parallel within a housing, and a control unit. The light source, mounted immediately above the tin strip, provides intense illumination over the full width of the strip. As the tin plate races through the shearing line at 1000 feet per minute, the detector automatically spots, classifies, and marks minute holes smaller than $\frac{1}{64}$ inch. The detection of these imperfec-

tions, most of which are invisible to the naked eye, prevents the use of unsuitable material and protects canned foods against leakage and spoilage. The equipment is arranged to indicate the presence of a hole by the operation of a signal light or bell, and if desired the defective portion of the plate may be marked

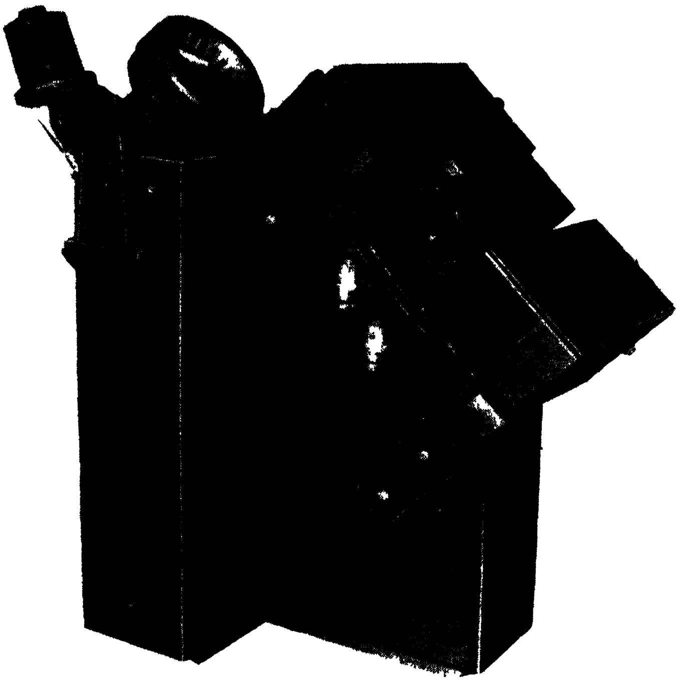


FIG 7-16. Photoelectric gauging and inspection machine. *Courtesy Electric Eye Equipment Company.*

by means of a stylus. The inspector operating the shear at the end of the mill can then cut away the defective portion of the sheet, or, if the material is sheared to length, the entire sheet can be reclassified and salvaged.

The versatility of photoelectric equipment in inspecting large quantities of fabricated parts may perhaps best be visualized by briefly reviewing several typical designs. The machine illustrated in Fig. 7-16 checks the over-all length of a machine part about $\frac{5}{8}$ inch long. Operating at an inspection speed of 120

pieces per minute, this machine maintains an accuracy of 0.0001 inch and sorts the parts into accepted and rejected lots. The gauging method is such that the part is rotated in the inspection position and tested for minimum length because infrequently a part has an off-square end due to the cutoff method employed. A continuous ring gauge is simulated on the diameter inspection and a snap gauge on the over-all length. This permits the sorting for objectionable taper and eccentricity, and allows for selectively sorting the rejects into various classifications.

Another apparatus, Fig. 7–17, consists of two machines in tandem designed to determine the presence of certain critical parts of a fuse assembly after loading. The presence of these parts determines the safety with which the component can be handled, and, since the fuse is loaded, it is necessary to determine the absence of these parts without actually firing the fuse. Each machine rotates the part at the prescribed speed and determines the position of two movable pins within an inner diameter of the part. The test in the first machine is extremely critical in that slight variations in the physical characteristics of the pins themselves may affect the results. The space between the pins is measured to the high accuracy of 0.0001 inch while the part is rotating. The second machine utilizes a clutch and brake method to bring the piece to the desired rotational speed, and, after braking to a stop, photoelectric inspection and sorting follow. In this machine the spindle speed is higher, resulting in a complete retraction of the pins, and they are retained there by a centrifugal lock dropping into position. The machine automatically determines that the lock is engaged. Production rate of each machine is approximately 60 piece parts per minute. It is self-evident that automatic inspection represents an economic advantage; the fidelity of the inspection machines was established when only one error was found in 4,000,000 pieces passed. In this installation, as well as in the previously described machine, the operator merely places the parts in a manual feeding chute, after which he has no control over the inspection and makes no decisions.

Photoelectric tests are not confined to solids only, since color, turbidity, viscosity, and other properties of liquids or gases may be measured with equal facility. For example, in an automatic viscosimeter operating on the photoelectric principle, the control

adds solvent or thinner when the viscosity of a printing ink reaches a predetermined point. Gravure inks are highly volatile, and a hydrocarbon such as benzol or naphtha is used as a

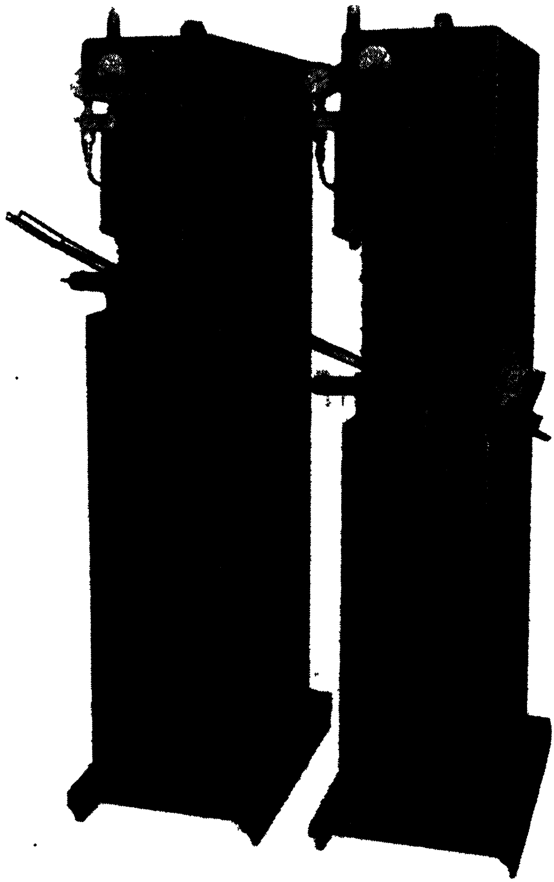


FIG. 7-17. Two inspection machines operating in tandem test dimensions of fuse parts to an accuracy of 0.0001 inch. *Courtesy Electric Eye Equipment Company.*

solvent to maintain the correct shade of ink as well as its drying quality. After a color printing press is placed in operation a photoelectric viscosimeter continuously checks the ink viscosity and adds solvent as required to maintain the proper viscosity.

7-6. Register Regulation

When packages are labeled from previously printed stock, or during the fabrication of labels, bags, and wrappers, a regulator must be used to insure that the cut in the stock occurs at the proper point with respect to the printed matter. Unequal shrinkage, stretch, and paper slippage prevent the maintenance of proper register even though the machine feeds paper at a constant rate to the uniformly operating knife. By means of a photoelectric register regulator, the printed paper is maintained in the proper position with respect to the cutter by regulating or changing the speed of the paper as required by controlling its drive. At the time of printing, a small register mark is included in the design or, preferably, on the margin, and prior to the cutting operation a phototube scans the stock for the register mark, making suitable correction in the feed if the position or distance of the mark from the cutter varies. High-speed corrective measures are necessary since paper speeds up to 1000 feet per minute are not uncommon. With such operating speeds it is impractical to change abruptly the nominal speed of the main roll, and the desired registry is obtained by advancing or retarding, by a corresponding shortening or lengthening of that portion of the web located between the main roll and the cutter, through the aid of a variable-speed device, or more commonly by means of a mechanical differential, which temporarily changes the speed of two auxiliary feed rolls, or in an alternate method controls a compensating roll. Of course, arrangements must be made to eliminate *hunting,* a term applied to alternate overcorrection first in one and then in the other direction.

A two-directional register regulator, Fig. 7-18, consists essentially of a photoelectric scanner that routes a periodic impulse after amplification to a two-circuit rotary selector switch operating in synchronism with the rotary cutter, the timing between them being so arranged that the register is correct if the selector switch is open when the impulse arrives. However, if the register is incorrect, that is, if the impulse arrives either early or late, the switch directs the impulse to either one of two thyratrons that control the operation of a reversing linestarter and the mechanical differential for a given time interval to retard or advance the web in relation to the rotary cutter. The action

repeats itself until the neutral register position is obtained; the sensitivity is of the order of plus or minus $\frac{1}{32}$ inch or better.

The scanner is of the compensated type and consists of two phototubes PT_1 and PT_2, the lamps with their optical systems, an amplifier tube V_1, and a potentiometer R_2 used for bias adjustment. The phototubes are arranged in a balanced bridge circuit, and, since both tubes respond the same to a decrease

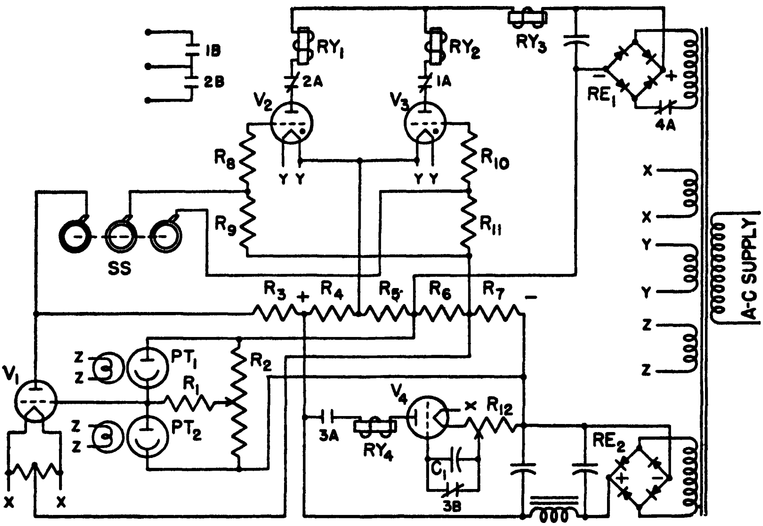


FIG. 7–18. Circuit diagram of a two-directional register regulator.

in illumination, such as may be caused by a change in tint, gloss, or finish of the paper, the output of the amplifier tube V_1 remains constant even though these factors vary. The phototube PT_1 is used as the control tube; a reduction in its illumination, caused by the interception of the reflected light by the printed spot, increases the internal resistance of the phototube and changes the grid bias of the amplifier tube to make it more negative, resulting in a smaller anode current. Later the spot intercepts the illumination reflected to the phototube PT_2, but this in turn causes the amplifier current to increase, an effect causing no control action. The output voltage that appears across resistor R_3 is impressed through the rotary selector switch *SS*, with the shaded sections of the rotors interconnected, on one or the other of the grids of the thyratrons V_2 and V_3. The dia-

gram, however, is drawn with the web in register, and in that case the rotary switch is in the open-circuit position.

When the illumination on the phototube PT_1 is momentarily decreased and the center contact of the selector switch completes the circuit, that is, if the web is out of register with the rotary cutter and the printed spot arrives too early, the grid of thyratron V_2 receives a positive impulse, the tube fires, the relay RY_1 operates, and the tube remains conducting until its anode circuit is opened. Closure of multiple contacts by the relay energizes the coil on a motor-reversing switch, causes the web to be retarded, and safeguards thyratron V_3 from operating. In addition to this, the operation of the relay RY_3 closes the anode circuit of the time delay tube V_4 and removes the short circuit across capacitor C_1. Depending on the value of capacitor C_1 and the setting of the resistor R_{12}, the highly negative grid potential gradually decreases as the capacitor charges until, after a definite time interval, tube V_4 conducts, resulting in the operation of relay RY_4. Contacts on this relay open the anode circuit of the thyratron by disconnecting the transformer secondary winding from the rectifier RE_1, and the release of the relays in the anode circuit of the thyratron restores the circuit to the original condition ready for another operating sequence if required. If the web needs correction in the opposite direction, the right-hand contact on the selector switch completes the circuit to the grid of thyratron V_3, and the reversing linestarter operates the mechanical differential in a reverse direction for the period of time governed by the operation of the time-delay tube V_4. A register regulator for a bag machine, illustrated in Fig. 7–19, shows the photoelectric scanner and the regulator. The latter controls the position of the design so that it will always appear in the proper place on the finished bag. The great advantage of register regulator installations lies in the reduction of waste and increased production obtained by higher operating speeds; in many cases photoelectric control has decreased waste by 50 per cent or more.

Cutoff register controls are only one type of adaptation of the many photoelectric applications in the fabrication and process control of sheet and roll stock. In this same family and similar in function are the weft straighteners, used in textile finishing mills to square the warp and weft by detecting skew in cloth

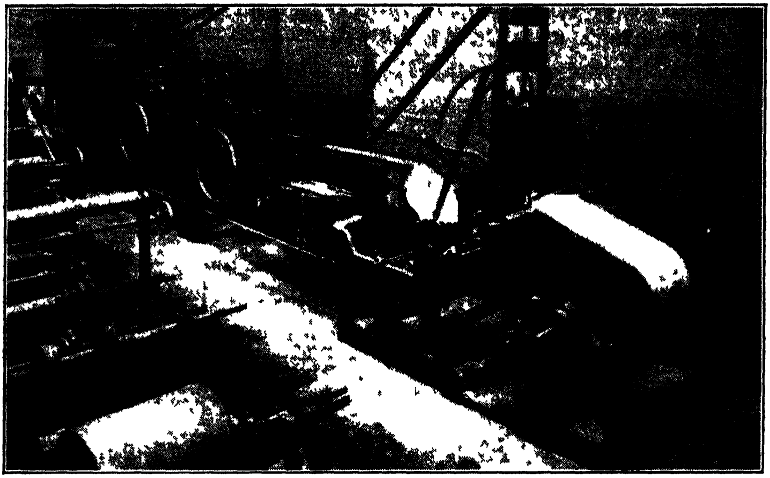


FIG. 7-19. Application of the two-directional register regulator to a bag machine. *Courtesy Westinghouse Electric Corporation.*

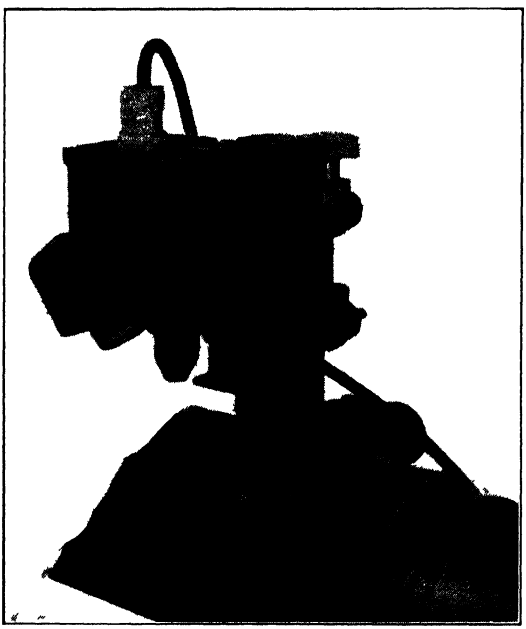


FIG. 7-20. Close-up view of a side-register scanning head applied to a paper winder. *Courtesy General Electric Company.*

and utilizing electric impulses to effect correction during weaving. Four or more colors are printed exactly over each other on multicolor presses to achieve full-color pictures by having a phototube note the passage of a color spot on the paper, then

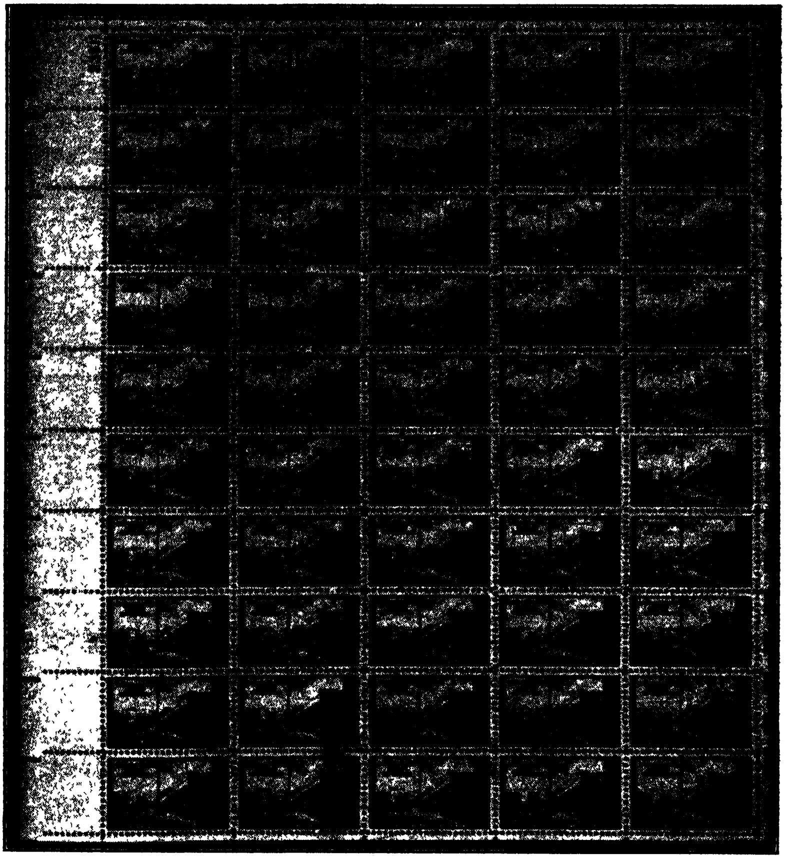


FIG. 7-21. Pane of commemorative postage stamps showing center and lateral register marks used with photoelectric equipment to aid in proper location of the perforations.

correlating the impulse with a similar one obtained by checking the position of the succeeding printing cylinder, and making the necessary correction in the speed of the web if they are out of register. This process is repeated between cylinders for each color.

Bread wrappers are printed in wide rolls, and, subsequently, a slitter cuts the paper to the correct width and removes a narrow margin at each side of the main roll. A scanning head, such as the one illustrated in Fig. 7–20, controls the side register by scanning the edge of the web, detects any variation from normal of the received light, and through an amplifier supplies power to a d-c motor which shifts the roll to maintain registration.

An interesting photoelectric application, described by A. W. Hall and listed in the references at the end of this chapter, is in the control of perforating United States postage stamps. These are printed by means of a rotary press on continuous rolls of paper. The intaglio steel plate process requires that the paper be soft and that it contain a high percentage of moisture in order that it may be depressed into the fine lines of the engraved plate to pick up previously deposited ink. During the subsequent drying, gumming, and redrying of the paper the printed work per impression changes in dimension with a possible variation of about $\frac{3}{32}$ inch in length and as much as $\frac{1}{4}$ inch in width. These deviations from normal require that, for the succeeding perforating operation, an operator adjust the mechanism continuously if the perforations are to be kept in the space between the stamps. Ordinary stamps are printed in sheets of 400 subjects; commemorative stamps of the type illustrated in Fig. 7–21 are laid out to the same sheet dimensions but contain 200 subjects, each sheet being ultimately cut into four panes. Center as well as lateral register marks are impressed on the web during printing.

After the rolls of paper are printed and gummed they are placed on a carriage in the perforator, a simplified sketch of which is shown in Fig. 7–22. Center register marks are scanned by the photoelectric device P_1, and correction is applied through a control C_1 and the motor M_1 to move the carriage sideways, if a variation exists, in order to maintain the register marks and the roll in an accurately centered position. The longitudinal perforations are produced by punch and die wheels, the outer ones being arranged for manual adjustment to bring them to their approximate position, but for final adjustment, a side register-type scanning head, located on each side of the web, controls their exact position to compensate for variations in the width of the printed stock. Lateral perforations are produced by a

cylindrical punch and die and are controlled by two photoelectric impulses, one from the lateral register marks printed on the web, and the other from light transmitted through slots located on a disc mounted to rotate with the cylindrical punch.

A cutoff knife operates in synchronism with the perforating cylinders and cuts the sheets to the proper length with the correct margins from the edge of the printed design. Auxiliary

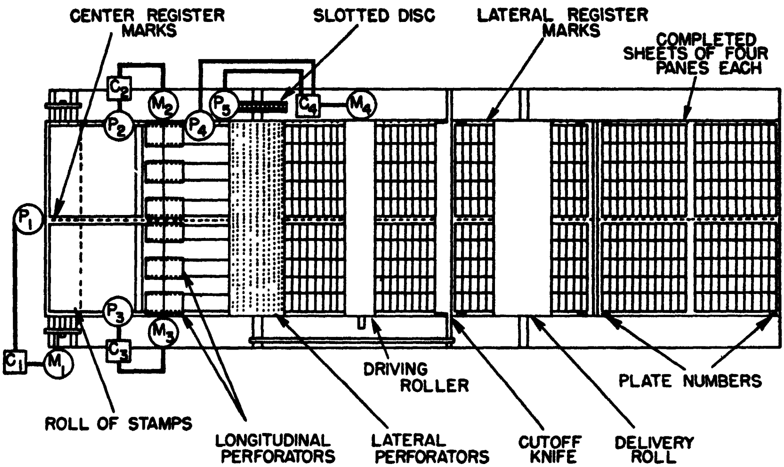


FIG. 7-22. Simplified sketch of the photoelectric register control on a postage-stamp perforating machine in use at the U. S. Bureau of Engraving and Printing. *Courtesy Electronics.*

manual-control switch buttons are located at various points on the machine to effect rapid correction for unusual and extreme paper variations. Well-centered stamps such as those shown are not only sought after by philatelists, but they also reduce the waste inherently present in the annual production of billions of postage stamps.

7-7. Motion Pictures with Sound

Motion pictures received a major impetus in 1927 with the introduction of music and dialogue; synchronized sound added realism to the presentation. Long-distance telephony, radiobroadcasting and radio reception, phonographs, public-address systems, and underwater signaling apparatus also utilize sound in connection with electronic equipment for the conveyance of

intelligence or for entertainment. But, before we consider these electronic applications, we shall review some salient features of sound.

Sound is a longitudinal wave motion in an elastic medium, which manifests itself as a sensation when received through the ears. Velocity of sound in air is about 1120 feet per second; in water it is approximately 4800 feet per second. The audible frequency spectrum extends over a range from about 16 cycles to 18,000 cycles per second, the average human ear being most sensitive to frequencies ranging between 800 and 1500 cycles per second. High frequencies contribute chiefly to the intelligibility of speech and brilliance in music; low frequencies carry much of the volume and add to the realism of reproduced sound. Along with other wave motions, sound also is subject to the phenomena of reflection, refraction, diffraction, and interference. The response of the human ear to sound is proportional to the logarithm of the power, usually measured in watts, producing the sound, but absolute loudness is not easily defined; it is much easier to compare the loudness of two sounds and to evaluate the difference. A common unit for this is the decibel, which is given by the equation

$$N = 10 \log \frac{P_1}{P_2} = 10 \log \frac{I_1{}^2 R_1}{I_2{}^2 R_2} = 10 \log \frac{E_1{}^2 R_2}{E_2{}^2 R_1}, \qquad (7\text{–}5)$$

where N is the number of decibels, and P_1 and P_2 are the power levels of two sounds. The other expressions follow directly from the power equivalents. Gain is given, in decibels, if the first sound is louder than the second and as a loss if the condition is reversed. The smallest change in sound intensity at 1000 cycles per second which the ear can detect is approximately 1 decibel. A logarithmic unit such as this has the advantage that transmission gains or losses of equipment operated in series can be added or subtracted directly.

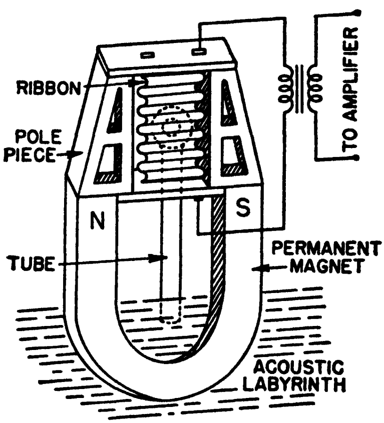
If the resistances are equal, as for example when each power is supplied to the same load, Eq. 7–5 becomes

$$N = 20 \log \frac{I_1}{I_2} = 20 \log \frac{E_1}{E_2}. \qquad (7\text{–}6)$$

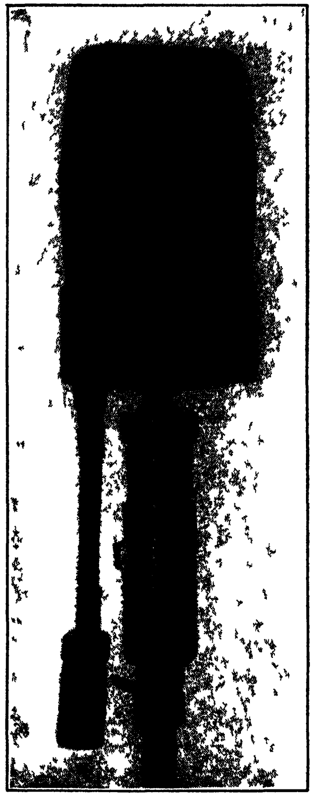
Recordings of sound on film are made by means of a microphone which converts the pressure variations in the air to cor-

responding electrical voltage changes that are amplified and then produce a variation in the light to expose photographically a soundtrack on the film. Many types of microphones have been developed. In the dynamic type a voltage is induced in a coil that is attached to a diaphragm and that moves in the magnetic field supplied by a permanent magnet. Its modification is the ribbon microphone, wherein the coil and diaphragm are replaced by a corrugated ribbon on which the sound wave can act directly. These two types are used extensively for radiobroadcasting and sound recording.

The sketch and photograph of Fig. 7–23 illustrate the ribbon microphone. An aluminum alloy ribbon,



(*a*)



(*b*)

FIG 7–23 Velocity or ribbon-type microphone. (*a*) Sketch of microphone showing ribbon and location of major components; (*b*) external view of ribbon microphone. *Courtesy Radio Corporation of America.*

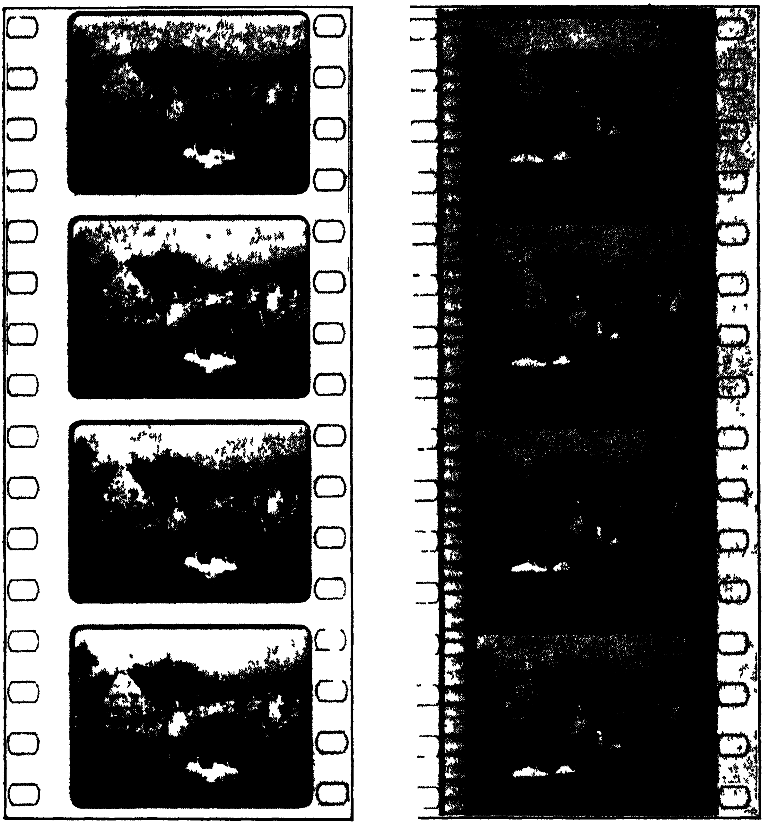
about ¼ inch wide, 2 inches long, and 0.0002 inch thick, serves as the diaphragm and the inductor; it is located between the pole pieces of a powerful permanent magnet. With both sides exposed, it moves in proportion to the velocity component of the sound wave; that is, it operates because of the pressure difference

between the front and back of the ribbon, and in doing so has a voltage induced in it which corresponds exactly to the sound wave in frequency and amplitude. Since its resistance is extremely low, an impedance-matching transformer must be used between the ribbon and the amplifier. The output of the microphone is quite low and, depending on the specific design, has a value ranging between 55 and 80 decibels below an arbitrarily established reference level of 0.006 watt. A tube and an acoustic labyrinth assist in obtaining a uniform frequency response from 40 to over 10,000 cycles per second; the characteristic droops below and above these frequencies. Ribbon microphones are easily overloaded, and, for the more severe outdoor duty, the more rugged dynamic microphone is frequently preferred.

The recording amplifier is of the high-quality type and contains sufficient gain to operate the recorder, commonly termed a *light valve,* which consists of one of two types to produce either a variable-area or a variable-density light recording or soundtrack on the film. A variable-area recording is made by means of a concentrated light source whose image is focused on a galvanometer mirror. As the mirror rotates in conformity with the changing signal current, the light image is reflected, causing a slit of constant width located in front of the moving film to have more or less of its area illuminated. This produces a constant-density but variable-width recording on the film, the normal position being that where one-half of the soundtrack is exposed. A variable-density recording, on the other hand, is obtained from a lamp whose light of constant intensity is focused on a very narrow slit which opens and closes in width according to the changing signal current and, consequently, produces exposure of a moving film located behind the slit. Such a recording has a variable density but a constant width on the film, as illustrated in Fig. 7–24. It is general practice in motion picture production to obtain the picture and sound on separate films and later to combine them on a single film. In this manner music may be added, sound effects may be combined, and the loudness and quality adjusted for optimum results.

In a motion picture film projector the soundtrack is scanned in the direct method by focusing a light source on a narrow slit which projects the light beam onto the film, the transmitted portion of the light passing through another lens and impinging

on the phototube. In the rear scanning method, the light is focused on the film and the transmitted light is passed through an objective lens and then through the slit before it reaches



(a) (b)

FIG 7-24. Black and white reproduction of four frames taken from the technicolor motion picture film, "When the Clouds Roll By." (a) Scenes as filmed without sound track; (b) variable-density sound track added at the left. *Courtesy Metro-Goldwyn-Mayer Pictures.*

the phototube. Figure 7-25 shows the details of a scanning mechanism operating on this principle, but with the light reflected by a lens mirror through a relay lens into the phototube. The normal speed of operation is 24 frames per second; two loops, one on each side of the device producing intermittent movement

of the film, take up major variations in speed as the film moves through the projector. Flutter or sound variation, caused by nonuniform motion of the film at the point of scanning, is additionally reduced by means of a rotary stabilizer. The repro-

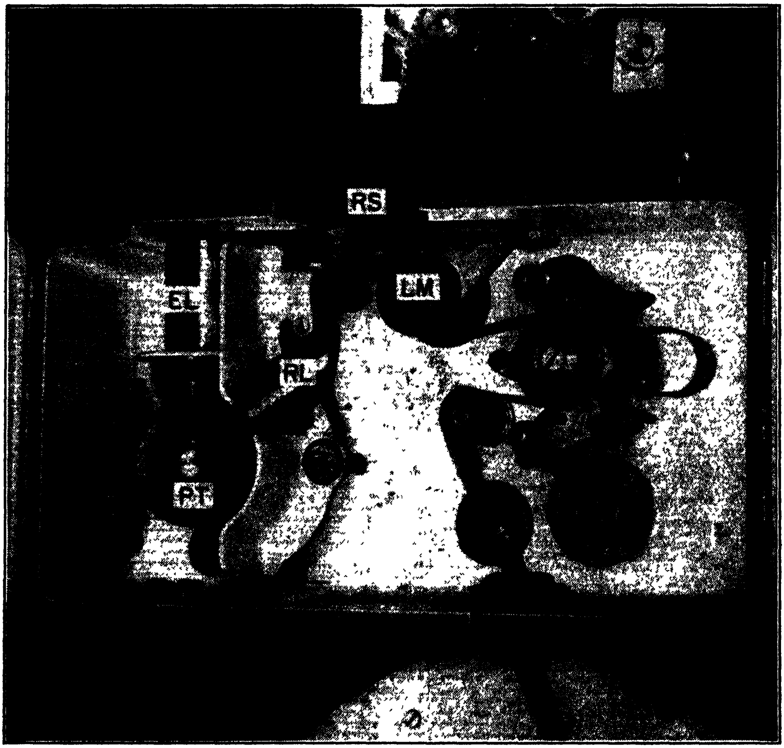


FIG. 7-25. Details of photoelectric scanning mechanism and reproducer portion of the Motiograph projector showing exciter lamp *EL*, lens mirror *LM*, relay lens *RL*, phototube *PT*, and rotary stabilizer *RS*. *Courtesy Motiograph, Inc.*

ducing amplifier is generally mounted in panel form and is of conventional design with its output power determined by the seating capacity of the auditorium. For high-quality reproduction the amplifier power must be adequate in order to keep distortion to a low value; the minimum recommended power varies from 20 watts for theaters seating 1000 to 132 watts for those seating 6000 persons.

The power amplifier delivers its energy to the loud-speaker, an electromechanical device that must reproduce audio frequencies from about 30 to 8000 cycles per second with high fidelity, that is, without the introduction of marked resonances or distortion. In the universally used dynamic or moving-coil loud-speaker, a molded, seamless, conical diaphragm actuates the air; it is driven by the amplifier output current flowing through a centrally attached coil located in a magnetic field supplied by an electromagnet or by a permanent magnet. The sound-reproducing requirements in an auditorium are much more severe than those in a radio receiver, and so the amplifier output passes through a dividing network that delivers the high-frequency energy to one or more loud-speakers specially designed to reproduce these frequencies, while the low-frequency energy is directed to another group of loud-speakers which need to respond only to that portion of the audible spectrum. The crossover point is not sharply defined; it is usually located somewhere in the region between 500 and 1500 cycles per second. A duplex loud-speaker system of this type suitable for a large auditorium seating 3500 persons is illustrated in Fig. 7–26.

The low-frequency unit consists of six individual speakers each equipped with a cone having an effective area of 123 square inches and driven by an edgewise-wound copper-ribbon coil 3 inches in diameter which moves in a field supplied by an Alnico V permanent magnet. In order to obtain effective coupling between the diaphragms and the air, as well as to improve the low-frequency response, the units are mounted beside each other in two large exponential horns. Ports, located in the front of the speaker and below the mouth of the horn, cause phase inversion and raise by several decibels the sound output at about 50 cycles per second. The high-frequency loud-speaker is composed of two smaller dynamic units mounted on a double throat connected to an exponential, multicellular horn located above the low-frequency loud-speaker. Each diaphragm is made from aluminum alloy and has a central vibrating portion nearly 2 inches in diameter; it can operate as a piston for high frequencies extending up to the limit of audition. A composite loud-speaker system of this type allows acoustic energy to be distributed throughout a vertical angle of 60° and a horizontal angle of 100°. With the loud-speaker mounted outdoors at a height of

40 feet, tests indicate that it has a linear response within 2 decibels from 80 to 5000 cycles per second, and that the response is not more than 5 decibels down at 50 cycles per second.

Sound on film also finds application on the narrower 16-millimeter film in the form of portable equipment for educational

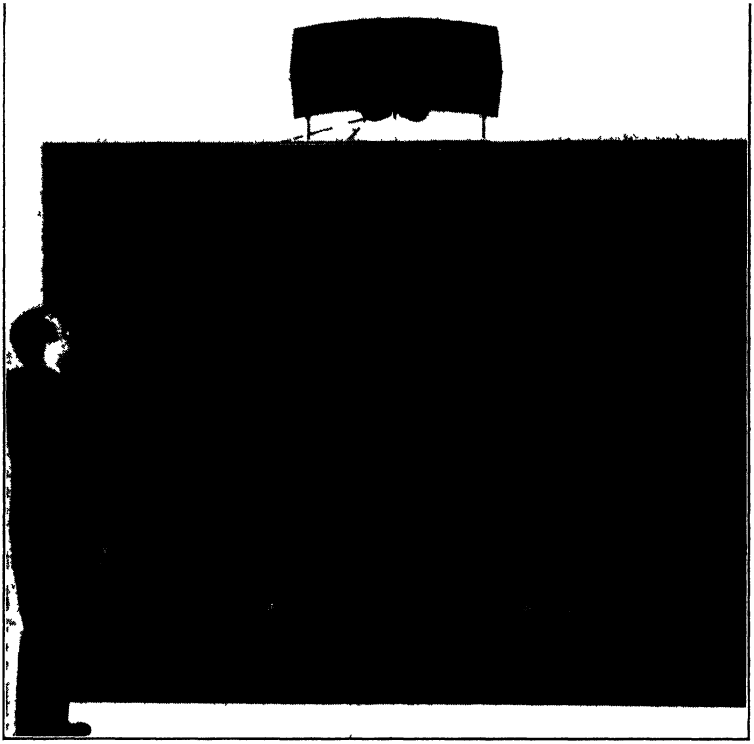


Fig 7–26 A theater-type duplex loud-speaker system consisting of six large dynamic units mounted within a horn, and two high-frequency units coupled to a multicellular horn. *Courtesy Altec Lansing Corporation.*

purposes in schools, for instructional work and safety campaigns in factories and industrial plants, and for entertainment purposes in transcontinental trains and transoceanic airplanes. The projector, shown in Fig. 7–27, incorporates the amplifier, the volume and tone controls, and the phototube; the portable loud-speaker shown at the rear is connected to the amplifier and is located near the screen to provide the illusion of realism.

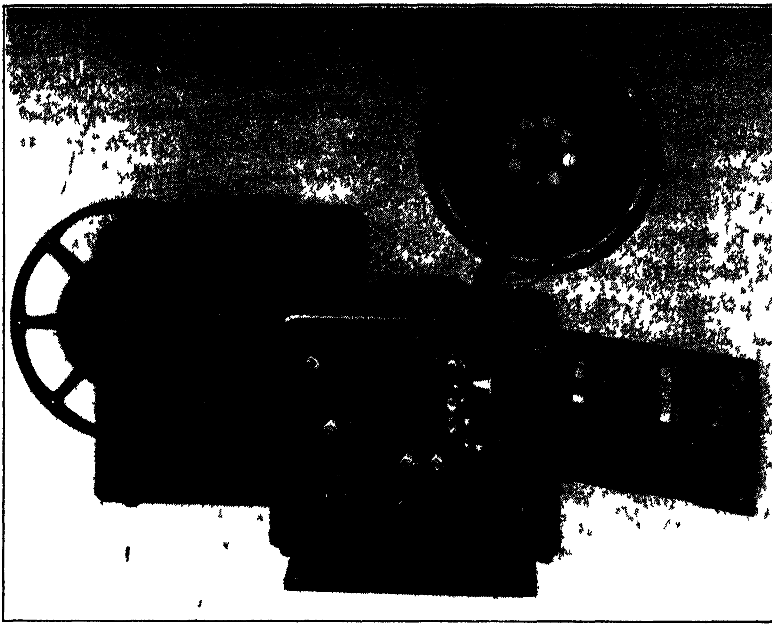


FIG 7-27 Complete 16-millimeter projector with amplifier and loud-speaker *Courtesy Bell & Howell Company*

7-8. Electron Multiplier Tubes

Secondary electron emission may be utilized to produce amplification by causing the secondary electrons to strike successive electrodes, termed *dynodes,* so connected that each is at a higher positive potential than the previous one and with the final intensified electron current terminating at a collector anode. Such a tube, known as an *electron multiplier tube,* is commonly equipped with a photoelectric cathode With the final anode at a high positive potential with respect to the cathode, an electron emitted by the cathode has a tendency to move directly to the collector anode; early multiplier tubes depended on a combination of electric fields and a magnetic field at right angles to each other to constrain the electrons to move in curved paths from one electrode to the next.

V K Zworykin and R A Rajchman have developed a photoelectric multiplier tube wherein the electrons are focused solely by electrostatic fields. A cross section of this tube, not much

different in size and shape from the ordinary phototube, is shown in Fig. 7–28. It is of the vacuum type and contains a photoelectric cathode 0 on which the incident light impinges, a group of nine dynodes 1 to 9, each capable of producing secondary electrons and designed so that the electrostatic field between them focuses the electrons onto each dynode in succession, and the collecting anode 10, shielded by dynode 9, on which the electron stream terminates.

Required potentials are conveniently obtained by connecting a group of ten resistors across a d-c power supply of 1000 to 1250 volts, connecting the cathode to the negative terminal, mak-

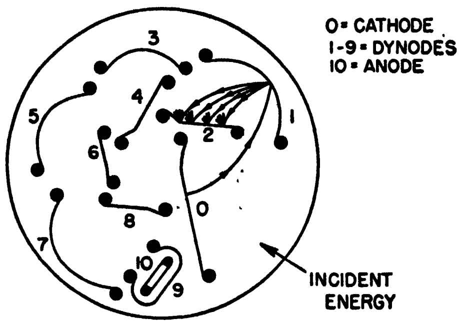


FIG. 7–28. Cross section of a photoelectric multiplier tube.

ing each dynode in succession more positive by about 100 volts, and making the collecting anode positive by 250 volts with respect to dynode 9. Since each emitted electron ejects as many as four or five secondary electrons, one original electron is multiplied between 200,000 and 2,000,000 times, depending on the magnitude of the voltages between the electrodes and the specific design. This inherent amplification results in an amazing sensitivity, and extremely low light excitations produce high outputs without the complexity of a number of high-gain amplifier stages. Signal-to-noise ratio for very low light levels is materially improved because of the absence of amplifier coupling components, and the frequency response is flat up to the limit determined by the transit time of the electrons, that is, well above 10 megacycles per second.

A unique adaptation for the multiplier tube lies in the field of quantitative measurement of X rays. By wrapping a standard multiplier tube with a fluorescent screen and over this a sheet

of black paper to eliminate ordinary light, the device, when connected to a proper power supply and with a suitable meter or relay in its output circuit, can be used for X-ray intensity measurements; it has the advantages of simplicity, speed, and continuity. This instrument, shown in the simplified sketch of Fig. 7–29, is used in automatic exposure timing for mass medical radiography. The multiplier tube V_1, indicated as a conventional tube, is connected to an amplifier tube V_2. A capacitor

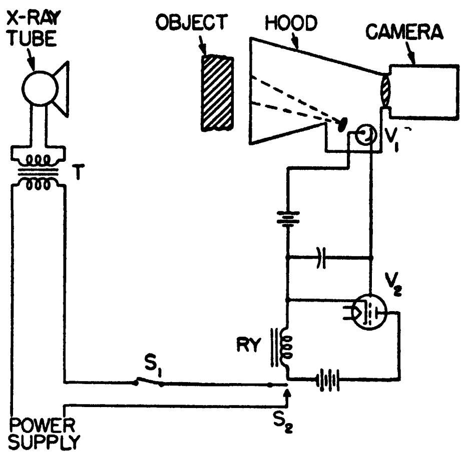


Fig. 7–29. Diagram of an automatic X-ray timer utilizing a photoelectric multiplier tube.

in the grid circuit of that tube determines the exposure time. The relay contacts S_2 are normally closed, and the exposure starts when the manually operated switch S_1 connects the power supply to the X-ray tube. During the exposure, the screen around the multiplier tube fluoresces, and the output current of the tube charges the capacitor until the potential on the grid of the amplifier tube reaches a point where the amplifier output current operates the relay and stops the exposure. The capacitor subsequently discharges because of grid current, and, if in the meantime the switch S_1 is opened, the circuit returns to its original condition.

7–9. Direct-reading Spectrometer

Although chemical analysis is commonly used, the spectrographic method is being employed to an increasing extent. For

example, it is utilized in foundry or blast-furnace practice, when time is at a premium as it is just before pouring the molten metal, or when a sample is to be tested for many minor constituents, a number of which may require much time and skill to segregate them from the major constituent. In this procedure, a spark is established by applying several thousand volts between two electrodes composed of the sample or between two carbon electrodes arranged so that the specimen, in particle or powder form, is vaporized between them. The resulting light is focused through a narrow slit onto either a prism or grating. A group of images of the slit are formed, depending on the wavelengths of the incident light, and a photographic film records the charac-

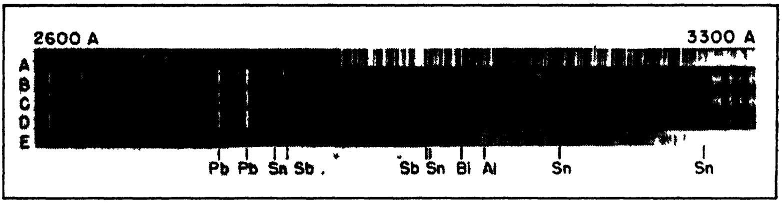


FIG. 7–30. Typical spectrogram of three lead alloys. Patterns *A* and *E* are reference standards.

teristic spectrum pattern and lines of the constituents of the unknown. After the film is developed, the position of the lines is compared with standard records; their position positively identifies any given element, and the intensity of the lines, for a given exposure, is a measure of the amount of the constituent present in the sample. Such a record provides a simple means of obtaining a qualitative as well as quantitative analysis; it can be made in 15 to 30 minutes. Figure 7–30 shows a typical spectrogram of 5 patterns, marked *A* to *E*, taken in the region between 2600 and 3300 angstrom units. Pattern *A* is the spectrogram of electrolytic iron, which is used for reference, and pattern *E* is a blank taken between carbon electrodes. Patterns *B*, *C*, and *D* were obtained from three sample alloys, each containing lead as a major ingredient to the extent of 94 per cent or more. Antimony appears as a substantial constituent in all three samples, but tin is found only in samples *C* and *D*. The film also discloses that various other elements are present in the samples, some of which are indicated in the figure.

Since the position and intensity of the individual lines form the basis for the analysis, the presence and quantity of each constituent of an alloy may be determined by providing an exit slit through which the light from a single or twin lines, if they are adjacent, of each element may be projected and focused on a photoelectric multiplier tube. Such a direct-reading spectrometer, shown in a simplified schematic drawing, Fig. 7–31, has

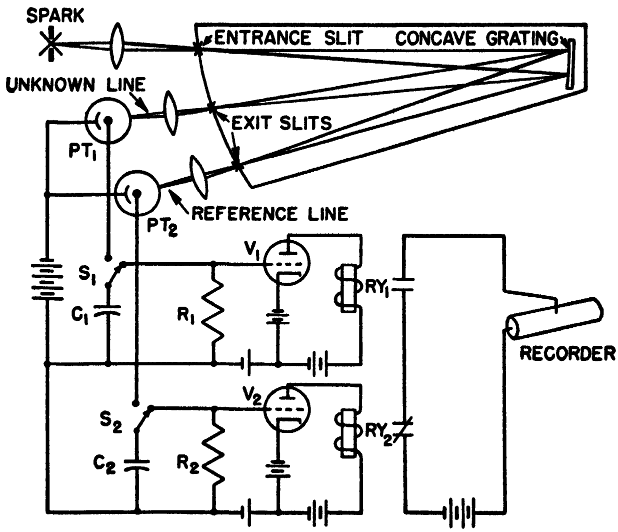


FIG. 7–31. Simplified schematic diagram illustrating the method of operation of the direct-reading spectrometer. *Courtesy Dow Chemical Company.*

been developed for the determination of aluminum, manganese, zinc, beryllium, iron, calcium, silicon, lead, nickel, and copper in a basic magnesium alloy. Only two of the eleven exit slits and electron multiplier tube circuits are shown in the diagram.

During the time the spark passes between the sample, capacitors C_1 and C_2 are charged by the current through each phototube to a value determined by the light intensities of the two spectral lines. At the conclusion of the sparking period, switches S_1 and S_2 are thrown simultaneously to the right-hand position, permitting the capacitors to discharge through resistors R_1 and R_2. Each capacitor voltage is impressed on a d-c amplifier, which is arranged to operate a relay in its output circuit when the capacitor or input voltage reaches a small fixed voltage

such as, for example, 1 volt as calibrated by a standard cell. This insures that each amplifier circuit causes relay operation at a definite grid voltage. The spectral line of the major constituent of the alloy—magnesium in this instance—energizes the tube connected to capacitor C_2, making the initial voltage on that capacitor greater than that on C_1, and, consequently, the voltage on C_1 reaches the predetermined potential of 1 volt before that on C_2. Contacts on relay RY_2 are normally closed while those on relay RY_1 are open, and the recorder circuit closes when the voltage on C_1 drops to 1 volt but opens later when the voltage on C_2 reaches the same value. The strip recorder, moving at a constant speed, records a line whose length is proportional to the difference in time required for the two capacitors to discharge from their initial voltage down to 1 volt. This time difference is a measure of the relative intensity of the two spectral lines and is used to determine the percentage of the unknown element in the sample by comparing its length with a calibrated rule or chart obtained by previous runs on an alloy of known composition.

The final instrument includes many optical, mechanical, and electrical circuit refinements impossible to consider in this brief description. The accuracy of analytical results is equal or superior to that obtained by the photographic method, and, since the entire operating cycle is automatic and requires only about 40 seconds, the speed and simplicity of the method are of great help in industrial laboratories where many analytical determinations need to be made daily.

7-10. Television Camera Tubes

Highlights and shadows of a single picture or film can be translated into a group of electrical impulses, for transmission either by wire or by radio, by having a phototube scan the subject in a manner similar to that by which one reads the page of a book. For television, however, where 30 scenes per second need to be scanned at a relatively low illumination, this method is inapplicable, and the requirement led to the development of several highly ingenious television camera tubes.

The *image dissector*, developed by P. T. Farnsworth and illustrated in Fig. 7-32, comprises a photosensitive cathode of the cesium oxide type and is arranged in an evacuated envelope

opposite an optical window. Each portion of the cathode emits electrons in proportion to the intensity of the impinging light. An eleven-stage electron multiplier, located just within the window, is equipped with a surrounding shield containing a square aperture through which the primary electrons enter. A positively charged coating on the inside wall of the tube acts as the anode that attracts the electrons emitted from the cathode, and a

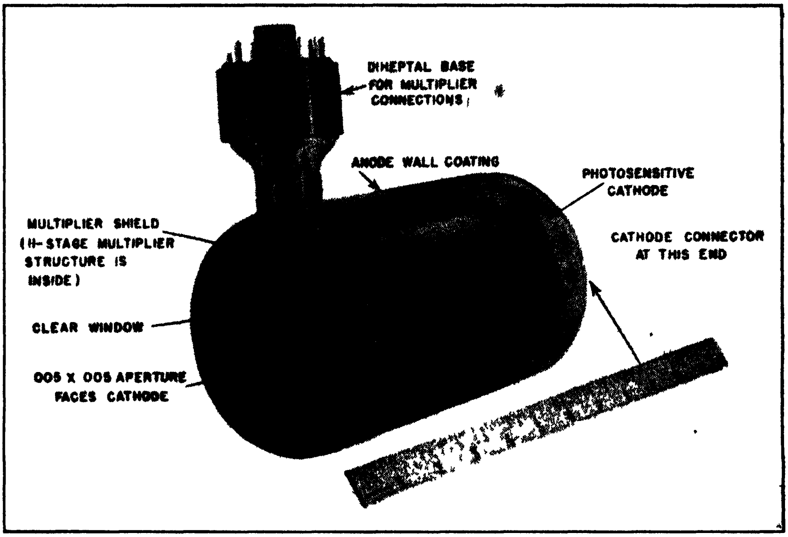


FIG. 7–32. The image dissector. Light enters from the left and is focused on the photosensitive cathode. *Courtesy Farnsworth Television and Radio Corporation.*

magnetic field, supplied by a coil surrounding the tube, focuses the extended electron image in the plane of the aperture so that the electron image extends outward from the cathode like bristles in a brush. Two additional magnetic fields, whose magnitudes vary in saw-tooth form with respect to time and which are arranged to be at right angles to each other, deflect the electron image horizontally and vertically across the aperture. The extended electron image is scanned across the aperture with the space current entering the aperture proportional at every instant of time to the electron density focused there. For that portion of the energy in the visible spectrum, the photosensitivity of the cathode is of the order of 20 microamperes per lumen, and with

a cathode illumination of 40 foot-candles approximately 10^{-10} ampere enters the aperture at any instant of time. The gain per stage in the multiplier is about 3.4 at 200 volts per stage, making the over-all gain about 1,000,000, so that the output current is about 0.1 milliampere. This changing output current as it flows through a resistor develops a corresponding voltage drop or signal

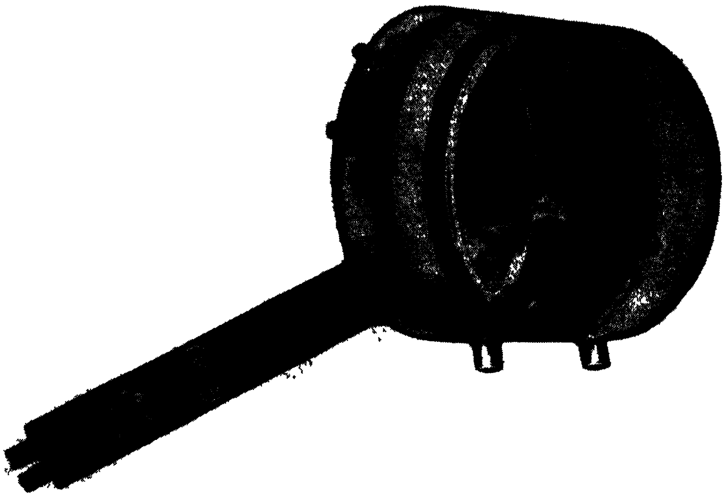


FIG. 7–33. An Iconoscope. Light enters from the left and strikes the photosensitive mosaic shown at the right within the tube. *Courtesy Radio Corporation of America.*

voltage which is amplified and transmitted. An electron image may be moved with reference to the aperture, that is, it may be scanned, at extremely high rates of speed. This is necessary since nearly 8,000,000 individual gradations of light and corresponding voltage changes may occur per second in an average 525-line television picture transmission.

The *Iconoscope,* a television camera tube illustrated in Fig. 7–33 and developed by V. K. Zworykin, is characterized by a mosaic-like light-sensitive surface composed of a multitude of closely spaced individual photosensitive spots located on a mica sheet and insulated from each other. A thin film of metal is sputtered on the reverse side of the mica sheet, forming the

companion capacitor plate for the hundreds of thousands of isolated photosensitive spots. In effect the surface consists of an enormously large number of miniature capacitors, each of which becomes charged when light strikes its surface because electrons are emitted in proportion to the intensity of the impinging light. An anode in the form of a conductive coating on the inside of the tube collects these electrons and subsequently

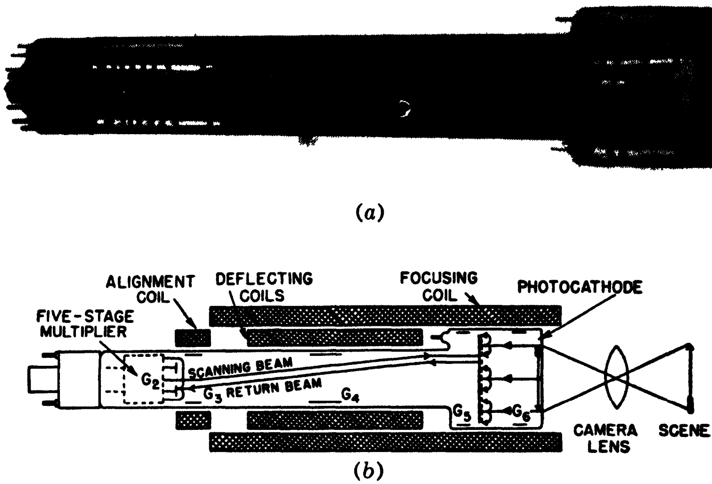


FIG. 7–34. (*a*) An Image Orthicon; (*b*) diagram showing the operation of an Image Orthicon. *Courtesy Radio Corporation of America.*

returns them by means of a beam of electrons projected by an electron gun arranged to scan the mosaic surface according to a predetermined sequence and at a given rate. During the scanning, the replacement of the charges produces identically corresponding voltage changes between the sputtered plate and the collecting anode. These variations are amplified and transmitted as the television signal. High picture quality and good resolution are obtained with the Iconoscope; it is adapted primarily for film and studio pickup service where relatively high illumination is readily obtained. A typical tube requires a mosaic illumination for highlights ranging between 1 and 10 foot-candles.

The *Image Orthicon,* announced in 1946 and shown in Fig. 7–34, is a television camera tube that has exceptional sensitivity,

good resolution for outdoor pickup, and good stability over a wide range of light levels. A suitable photocathode illumination for highlights for the type 2P23 tube ranges from the very low value of 0.01 to the high light level of 10 foot-candles. A semi-transparent conducting photoelectric cathode releases the electron image in accordance with the intensity of the impinging light. A corresponding, but fivefold greater, charge pattern is established by secondary emission from the electron image focused on the target by means of a uniform magnetic field supplied by a focusing coil. The target has two sides; the charge pattern is formed on one while the scanning takes place on the other side. It consists of a very thin sheet of low-resistivity glass, with the resistivity and the thickness chosen so that electrical charges developed on opposite sides neutralize each other by conduction during the time required for the transmission of a complete frame, that is, $\frac{1}{30}$ second, but during that time the charges do not spread sufficiently to impair the resolution of the charge pattern. An extremely fine-mesh stainless-steel screen with an open area of 50 to 75 per cent is mounted near the glass target to collect the secondary electrons. Simultaneously with the formation of the charge pattern on one side of the target, a beam of electrons, projected from an electron gun and deflected by suitable magnetic fields, scans the opposite side. As the electrons in the beam approach the target, they are decelerated and deposited to neutralize the positive charges of the pattern. Excess electrons in the beam, not required for neutralization, are reflected back toward their origin, because of the action of the magnetic field, and strike the defining aperture disc of the electron gun with sufficient velocity to produce secondary electrons. The disc, arranged as shown in the figure, acts as the first of a five-stage electron multiplier where the video signal is amplified and delivered for transmission in the same way as previously described. This method of construction and the signal multiplication permit the tube to approach closely the limit of camera-tube sensitivity; it is from 100 to 1000 times as sensitive as the Iconoscope, relatively free from spurious signals, and completely stable at all light levels. The commercial production of this extremely complex tube, as a standard item, represents a distinct triumph for tube-development, design, and production engineers.

In order to prevent flicker, scenes are scanned horizontally, left

to right, starting at the upper left, viewing all picture elements in the odd-numbered lines throughout the scene and then shifting to the even-numbered lines, alternately interlacing the two. Special cathode-ray tubes, also termed *Kinescopes,* follow the same scanning sequence at the receiver. A flyback period, during which the beam travels from right to left, and another interval, during which it travels from the lower right corner of the image to the upper left, are provided. Four accurately timed pulses are mixed with and transmitted in addition to the video signal from a television camera to insure synchronization between the transmitted and the received images. These are a frame synchronizing pulse at 60 cycles per second, a line blanking pulse at 15,750 cycles per second, combined line and frame blanking pulses, and a standard 525-line synchronizing pulse properly timed with respect to the blanking pulses. These pulses do not interfere with the picture signals because they are sent at a time when picture elements are not being scanned.

7–11. Infrared Beam Projector and Viewer

Infrared radiation is also capable of producing an electron image when a photosensitive surface which responds to such radiation is irradiated. This basic idea has been applied in the development of a device to make vision possible in total darkness; it was produced in various models and extensively employed during World War II in such activities as secret signaling between ships, automobile night driving, and other land and marine operations. The device is made possible by an *electron-image tube* which operates on reflected infrared radiation and converts an invisible infrared image into a visible image. The tube, illustrated in Fig. 7–35 and shown in cross section in Fig. 7–36, consists of three major components, a semitransparent, infrared-sensitive cathode, an electrostatic lens system, and a fluorescent screen. An infrared image on the cathode causes electrons to be released in proportion to the density of the image, and these electrons are accelerated and focused by the electron-lens system onto the fluorescent screen where a visible reproduction of the original image is formed. The spectral response of the photoelectric cathode extends beyond 12,000 angstrom units but has its maximum sensitivity at approximately 8000 angstrom units.

In processing the cathode an extremely thin semitransparent layer of silver is evaporated on the inside glass surface. The

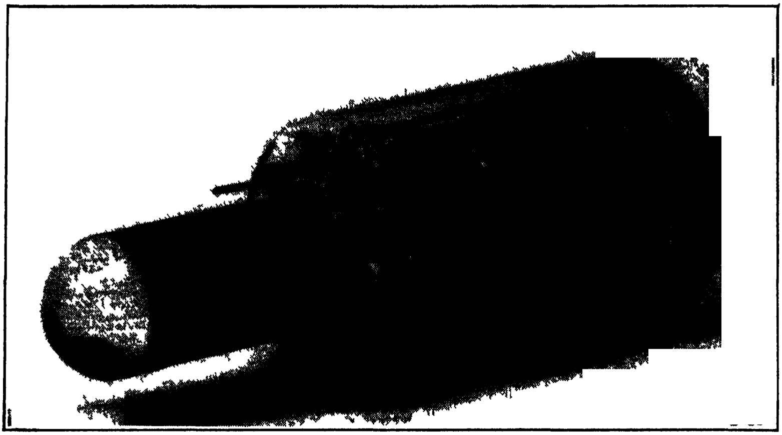


FIG 7-35 An electron-image tube. The cathode is at the right and the fluorescent screen is at the left. *Courtesy Farnsworth Television and Radio Corporation*

silver layer is then partly oxidized, exposed to cesium vapor, and subjected to a thermal treatment that causes the cesium to react with the silver oxide to form cesium oxide and free silver. The

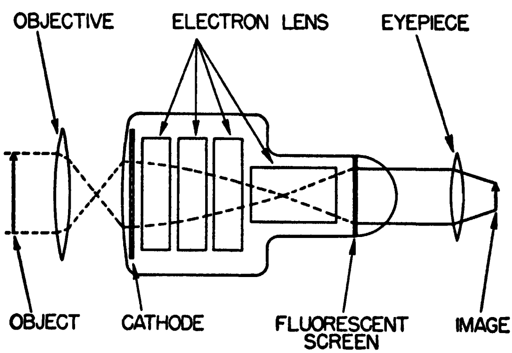


FIG 7-36 Cross-sectional view and diagram showing the major components of an electron-image tube and method of operation

final surface consists of silver, a layer of mixed silver and cesium oxide with interspersed metallic silver, and a bound layer of cesium.

The electron lens consists of four electrodes and is similar to the electron lens system in the electrostatically controlled cathode-ray tube. Synthetic willemite, which can be deposited with a fine grain for high resolution, has high efficiency at low-current density, and has high chemical stability under the operating conditions of high voltage and high vacuum, is used as the coating material for the fluorescent screen.

The circuit of a battery-operated infrared viewer is shown in Fig. 7–37. A small vibrator-interrupter, composed of the transformer T and the vibrating contacts RY, is energized by the bat-

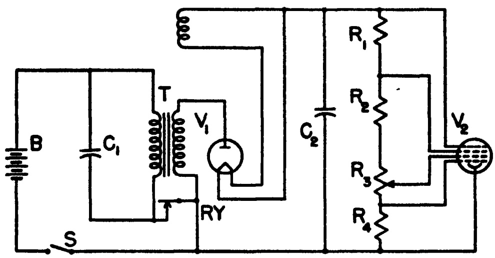


FIG. 7–37. Circuit of a battery-operated infrared viewer using an electron image tube.

tery B when the switch S is closed. It supplies the a-c power to light the filament of the rectifier tube V_1 and a high alternating voltage, which is rectified by the tube. The direct voltage, having a value of 4100 volts, is impressed across a resistance network that has suitable taps to deliver the required voltages for the electron lens system of the image tube V_2. Despite the high operating voltage, the complete power-supply unit weighs less than 2 pounds, and, since the power requirements are low, portable designs have been constructed which are energized by a single storage cell no larger than a flashlight cell, but which have a life of 1 to 2 hours of continuous operation. A larger model, operated from a 110-volt supply line and used for signaling between ships, is illustrated in Fig. 7–38. Still other models illuminate the object by infrared radiation from an ordinary tungsten lamp. Visible light is completely blocked out by a filter, and only the invisible radiation is allowed to flood the scene, permitting the electron image tube to pick up the reflected image.

The sensitivity of the tube is such that it can detect a star of the fifth magnitude, that is, a radiation equivalent to about $\frac{1}{10}$

candlepower, at a distance of 1 mile. The image definition, based on television nomenclature, is 450 lines at the center of the screen and 300 lines at the edge. In industry, an important

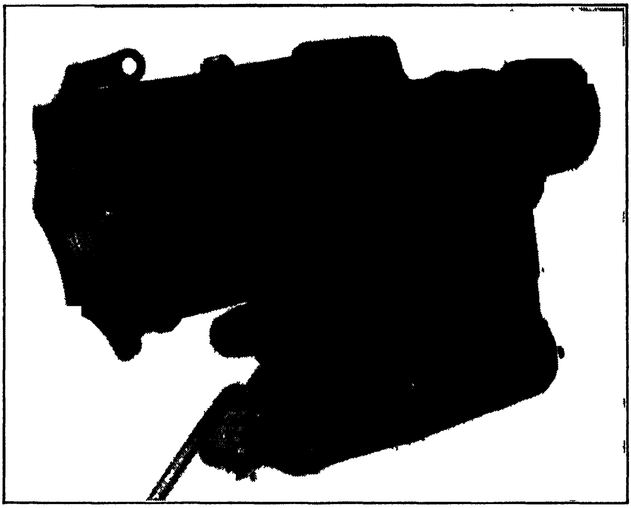


FIG. 7–38 A power-operated infrared telescope used for signalling between ships. *Courtesy Farnsworth Television and Radio Corporation.*

application for an infrared projector and viewer is in film-processing plants where the process must be viewed during manufacture, and coating and inspection must be done in darkness in order not to fog the photographic emulsion.

7–12. Photoconductive and Photovoltaic Cells

The electrical resistance of certain materials decreases appreciably during illumination; these substances are used in the construction of *photoconductive cells*. The light-sensitive material is mounted in a glass envelope which is equipped with a base similar to that of a conventional vacuum tube. Impinging light liberates electrons within the material; no electrons are emitted from the surface, but a variation in resistance takes place. Photoconductive cells are either of the selenium or the thalofide type. The selenium type is made by winding two wires, each in the form of a helix, on a flat insulating base and applying selenium between and over the wire. After heat treatment, the selenium is modified to the gray, crystalline form, and the unit

is mounted in a glass envelope; the ends of the wires are the electrical terminals. The thalofide cell uses thallium oxysulfide as the photoconductive material. It is deposited on an insulating plate in the form of a powder and melted to produce a thin layer. Appropriate terminals make electrical contact with the surface.

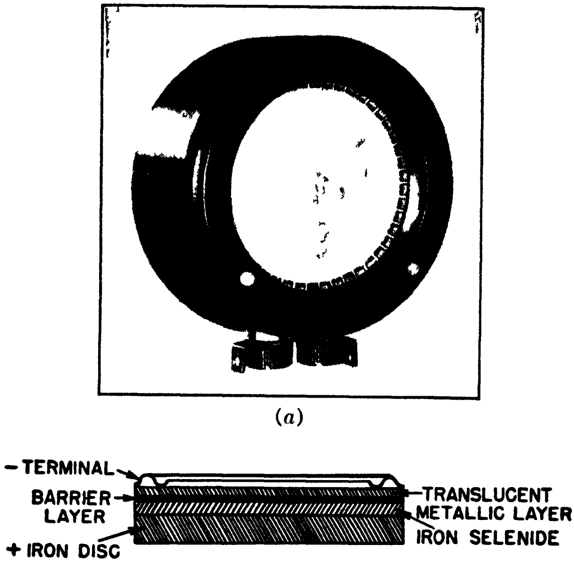


FIG. 7–39. (a) Photronic cell mounted in a Bakelite case and equipped with threaded terminals. *Courtesy Weston Electrical Instrument Corporation.* (b) Major components of a selenium-iron photovoltaic cell.

Chemical stability is obtained by inserting an inert gas into the tubes, and deterioration is prevented by the use of optical filters that confine the illumination to a definite band of wavelengths.

Photoconductive cells have relatively high resistance; an impressed voltage of 100 volts causes a current of about 150 microamperes to flow under normal illumination. Their spectral response varies with the type of surface, but they usually cover the range between 4000 and 12,000 angstrom units, with a marked response in the infrared region. For a specific applied voltage, the current of a photoconductive cell is not directly proportional to the illumination. The cells are sluggish in performance, requiring an interval of several seconds and sometimes minutes

for the current to reach a stable value during and after illumination.

The photovoltaic effect, that is, the generation of an electromotive force between two electrodes which are immersed in an electrolyte and illuminated, is not new; it was discovered by H. Becquerel about a century ago, and since then various *photovoltaic cells* have been developed. The effect also occurs if the interface between certain solid substances is illuminated. Iron selenide and cuprous oxide cells are the two major types, and since similar units form the foundation for dry-plate rectifiers it appears that the interface, or barrier layer, is, in some still not

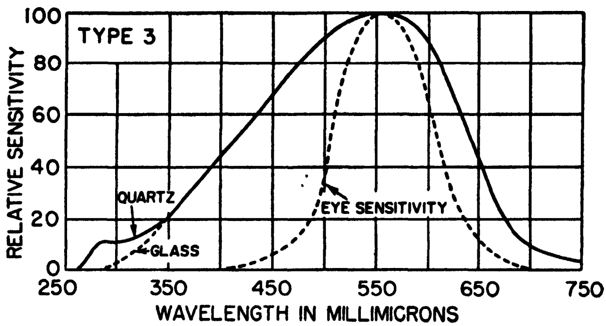


FIG. 7–40. Spectral sensitivity curves of a typical Photronic cell with quartz and glass windows.

well understood manner, responsible for the rectifying as well as the photoelectric effect.

In the Photronic cell, shown in Fig. 7–39, an iron-disc electrode is coated with a layer of iron selenide, and on this is placed a thin, semitransparent conducting film for the other electrode. The complete assembly is mounted in a Bakelite case and arranged so that the film can be illuminated through a window. When the light-sensitive interface is illuminated, an electromotive force is generated, with the iron disc as the positive terminal and the semitransparent coating with its terminal ring as the negative terminal. The cell has an internal, parallel resistance of about 10,000 to 20,000 ohms while darkened and an internal series resistance of about 50 ohms. A capacitance of the order of 0.5 microfarad exists between the electrodes.

The spectral response of an average cell is given in Fig. 7–40. Optical filters are available which, when used in conjunction

with these cells, yield a spectral response that closely approximates that of the eye. Current output of a Photronic cell varies with the incident radiation and the resistance of the external circuit, as shown in Fig. 7–41. Since the internal resistance of the cell is in effect in parallel with the load, it is apparent that the greatest current output, as well as linearity of current versus illumination, is obtained with a low-resistance load.

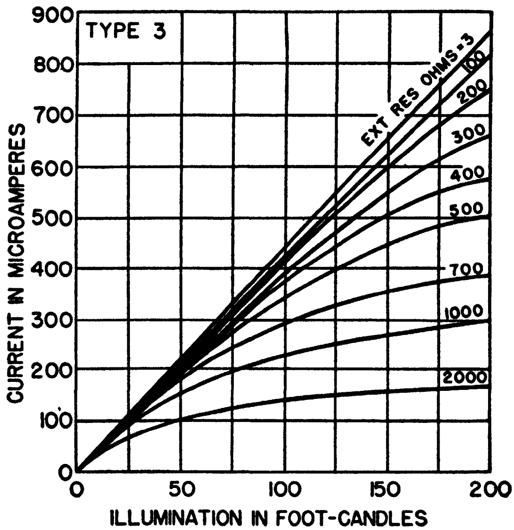


Fig. 7–41. Effect of illumination and external resistance on current output of a typical Photronic cell. Source of illumination is a tungsten lamp with filament at 2700° K. *Courtesy Weston Electrical Instrument Corporation.*

Two or more photocells may be connected in parallel to produce a current in the circuit equal to the sum of the components contributed by the individual cells. A portable, direct-reading illumination meter equipped with a light target that houses two Photronic cells, is illustrated in Fig. 7–42. A switch located on the side of the instrument permits the selection of the proper scale for the illumination intensity. High internal capacitance of these cells has prevented their application in circuits where the light is modulated in excess of several hundred cycles per second. However, their ruggedness, simplicity, and stability, coupled with the fact that no extraneous source of power is required, have resulted in their widespread use for photographic exposure meters,

sightmeters, and for various remote indicating and control devices, such as those used in connection with smoke elimination problems in power plants and sludge level control in water settling tanks.

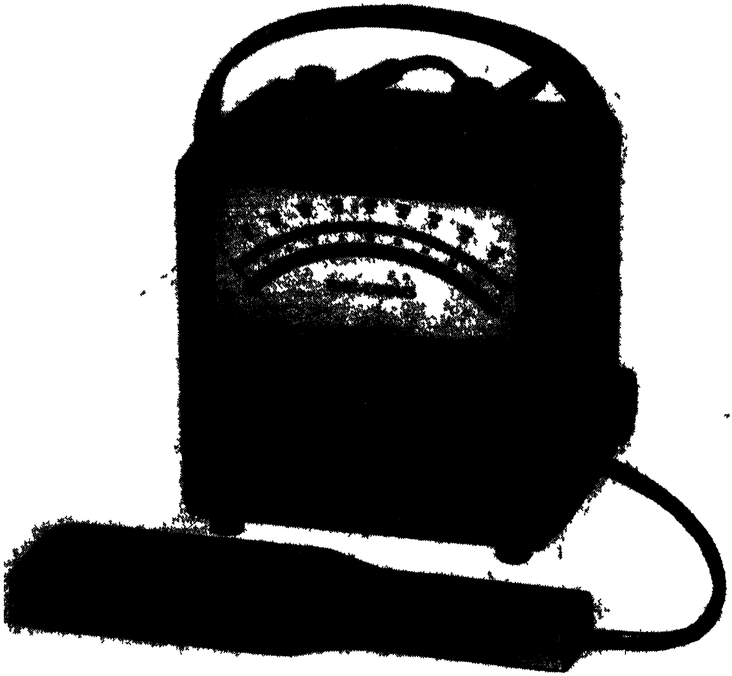


FIG 7–42 Portable direct-reading illumination meter equipped with a light target consisting of two Photronic cells *Courtesy Weston Electrical Instrument Corporation.*

The Photox cell consists of a copper electrode, oxidized on one side, and coated with a thin, semitransparent metallic film which serves as the other electrode. In mechanical form and shape it is quite similar to the previously described cell, and its electrical characteristics are not much different, except that the spectral response of an average cell is somewhat narrower. It responds to wavelengths between 4200 and 6700 angstrom units, and its color response closely approximates that of the human eye. The

life of photovoltaic cells of the barrier-layer type appears to be indefinite under normal conditions of use, and like dry-plate rectifiers they are apparently true electronic devices.

Problems

1. The WL-767 phototube has a titanium-on-nickel photoelectric surface with a work function of 3.87 electron volts. Will the tube respond to light in the range from 4000 to 7000 angstrom units? What is the threshold wavelength for this surface?

2. What is the maximum speed of electrons emitted from a potassium surface having a work function of 1.55 electron volts, when the surface is illuminated by light that has a wavelength of 5430 angstrom units?

3. The recently developed zirconium oxide concentrated-arc lamp is a point source of light for all practical purposes. (*a*) Prove that the intensity of light from such a source striking a phototube varies inversely as the square of the distance between them. (*b*) If an infinitely long lighted filament is used, how does the intensity of light at right angles to the filament vary with respect to the distance? (*c*) How does it vary if an infinitely large surface is the source of the illumination?

4. Plot the curves of output current versus luminous flux for various anode voltages, from the anode diagrams of the vacuum phototube, Fig. 7–2, and the gas-filled phototube, Fig. 7–3.

5. Redraw the circuit of Fig. 7–7(*a*) but add a full-wave vacuum-tube rectifier for d-c operation, replace the thyratron with a screen-grid vacuum tube, and substitute a neon glow lamp for the relay.

6. A press is equipped with a light curtain that has a circuit like that shown in Fig. 7–12. It operates satisfactorily for several weeks, after which the foreman notices that dust has settled on the lamps and on the phototubes. He telephones and expects answers from the engineering department to the following questions: (*a*) Has the accumulation of a thin layer of dust affected the sensitivity of the safety device? (*b*) How effective will the device be if he has the lamps cleaned, but not the phototubes?

7. Explain in detail how a positive grid voltage is obtained on tube V_1 in the two-direction register regulator circuit, Fig. 7–18, when the illumination on phototube PT_2 decreases, and why the corresponding voltage pulse causes no operation of either of the thyratrons.

8. A motion picture amplifier delivers a voltage of 80 volts at a frequency of 800 cycles per second and 20 volts at a frequency of 90 cycles per second to a constant-resistance network. What is the decibel loss in the amplifier between these frequencies?

9. In your opinion, what are the technical advantages and disadvantages of a variable-density, as against a variable-area, sound recording on film?

10. A type 3 Photronic cell, when connected to a 100-ohm microammeter, has the following shunting internal resistances for various illuminations: 22,000 ohms when dark, 3700 ohms at 100 foot-candles, 1700 ohms at 200 foot-candles, and 1000 ohms at 300 foot-candles. Calculate the terminal voltages of the cell for the four cases and plot curves on semilogarithmic

cross-section paper of the internal resistance and the cell voltage against illumination in foot-candles.

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8

Electronics in Instrumentation

Measurements are an important part of science and are indispensable to its growth. More refined instruments must be developed constantly to evaluate the more minute, the less obvious, and the more complex phenomena of nature which present themselves every time the horizon of human knowledge is extended. Emission and control of electrons in vacuum tubes, thyratrons, and phototubes have given us an entirely new approach and the foundation for a completely different group of instruments. Electronics supplies the research worker in nearly any field of science with a reliable means for obtaining precise and accurate data, and since processing and instrumentation in industry are absolutely interdependent, electronic principles are applied by engineers to produce a more economic and technically superior product. Several electronic instruments, such as the oscilloscope, the stroboscope, the electronic timer, the electron microscope, the mass spectrometer, and the light meter, were mentioned previously; here we shall review still others that are used in widely diversified fields of science and industry.

8-1. The Ionization Gauge

The manufacture of millions of electric lamps and radio tubes has given a tremendous impetus to the development of high-vacuum equipment and also to instruments for the rapid and accurate measurement of absolute pressures. As a result, absolute pressures in the range of fractions of a millimeter or even a micron of mercury pressure are today commonplace in industry.

The thermocouple-type gauge, which depends for its operation

on a voltage generated at the junction of two dissimilar metals in contact with a filament heated by a constant voltage supply, is used to measure pressures from about 0.5 millimeter to 0.001 millimeter (1 micron) of mercury pressure absolute. In this device, the heat loss of the filament varies with changes in the

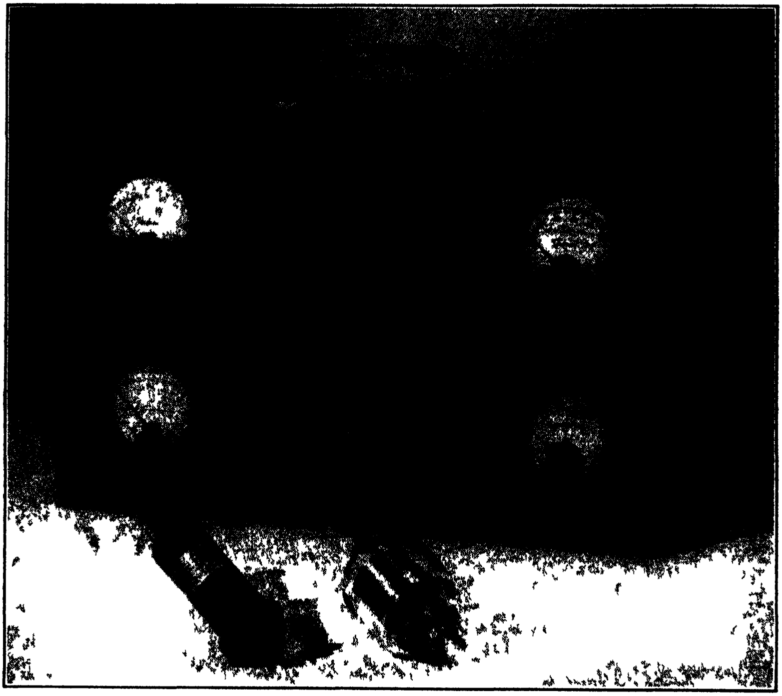


FIG. 8–1. Composite thermocouple and ionization vacuum gauge. *Courtesy National Research Corporation.*

thermal conductivity or with the pressure of the surrounding atmosphere. The Pirani gauge consists of a coil of resistance wire that acts as one arm of a Wheatstone bridge and which is mounted in an envelope connected mechanically to the vacuum system. With suitable temperature compensation, it is capable of measuring comparable pressures. However, for extremely high vacuums, where the pressures range between 1 and 0.001 micron of mercury pressure absolute, the *ionization gauge*, consisting of a triode comprising a filament, grid, and collector plate, is commonly employed. The gauge is connected with about 100

volts between the cathode and the grid, the grid being positive with respect to the cathode, and with about 20 to 30 volts between the cathode and the collector plate, with the collector plate negative with respect to the cathode. Electrons emitted from the hot filament are accelerated toward the grid; they collide with gas molecules, and the resulting positive ions migrate toward

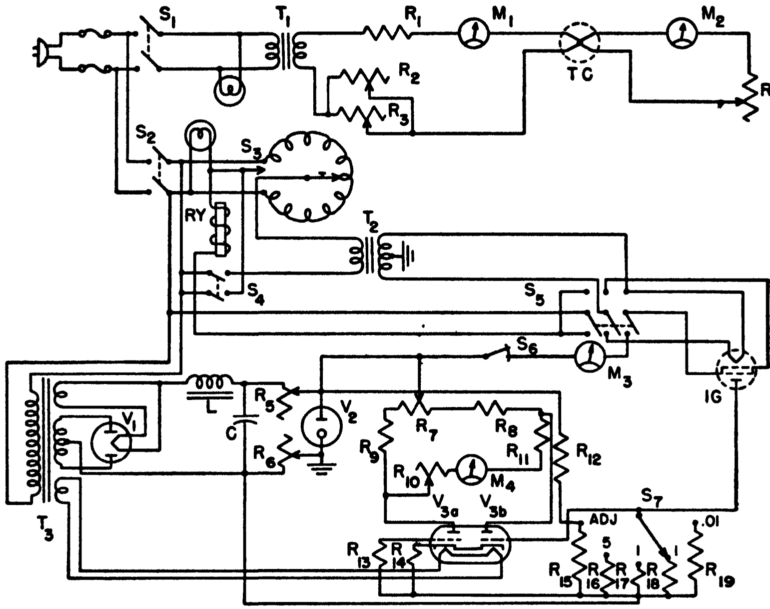


FIG. 8–2. Circuit of the composite vacuum gauge.

the plate, where they produce an ion current. This current varies with the gas pressure and actuates a microammeter in the collector-plate circuit.

A composite thermocouple and ionization-gauge instrument with its two gauges is illustrated in Fig. 8–1. In the circuit, Fig. 8–2, the thermocouple gauge is shown in the upper and the ionization gauge in the lower portion of the diagram. Current through the filament of the thermocouple *TC* is indicated by milliammeter M_1 and held constant; the pressure in the vacuum system, which may vary from 1000 microns to 1 micron, is indicated by meter M_2. The ionization-gauge circuit is provided with an amplifier and a voltage-regulated power supply. Four ranges indicate full-scale pressures of 5, 1, 0.1, and 0.01 micron

of mercury pressure directly on meter M_4 in the output circuit of the amplifier.

The tungsten grid has two terminals, and the circuit is arranged so that, when switch S_5 is thrown to the upper position, the filament current flows through the grid and removes any occluded gases prior to use. An interlocking relay, operated by the adjusting knob for the ion grid current, makes it impossible to energize the filament until the grid-current control is returned to zero, thus protecting the filament from burning out if the pressure in the gauge is too high. The "zero set" button and the "zero adjust" knob allow the amplifier to be balanced at any time. With a normal grid current of 5 milliamperes, the lowest pressure measurable on the ionization gauge is 2×10^{-4} micron of mercury pressure absolute. The anode-current gas-pressure characteristic for dry air of the ionization gauge is linear when plotted on logarithmic paper. Heat losses of a filament in a thermocouple gauge or in the resistance element of a Pirani gauge vary in a complex manner with respect to gas pressure, and, consequently, such gauges have irregular calibration curves.

8-2. Electronic Counters and Computers

Mechanical methods of counting and computing have been developed over many years and find application in the many machines used in every large office. As need arose for greater speed, and as problems became more complex, electronic devices were designed to provide more rapid but still highly dependable and accurate means for counting and totalizing. With a suitable fixed-frequency a-c input a simple counting device of this type may also be utilized for accurate high-speed timing; counting rates up to 20,000 per second are readily obtained.

Custom dictates counting in terms of decades. The least number of digits taken singly or that can be added to form all numbers between 1 and 9 is four, and so counters have been designed that use the four numbers of the binary geometric progression 1-2-4-8. Their basis of operation is the *trigger* or *flip-flop circuit* developed in 1919 by W. H. Eccles and F. W. Jordan; it is also the foundation circuit for the multivibrator. As shown in Fig. 8-3, a single decade circuit comprises four twin triodes with each tube acting as the control for the specific digit marked alongside each of the four indicating neon glow lamps.

The individual tube circuits are identical, and all cathodes are at a fixed potential of +150 volts with respect to the ground or negative terminal of the d-c power supply. Grid and anode potentials are obtained from taps on a resistance network, connected between the 300-volt line and the ground. They change in value as the current varies through the resistance network, and they change depending on whether or not a tube conducts.

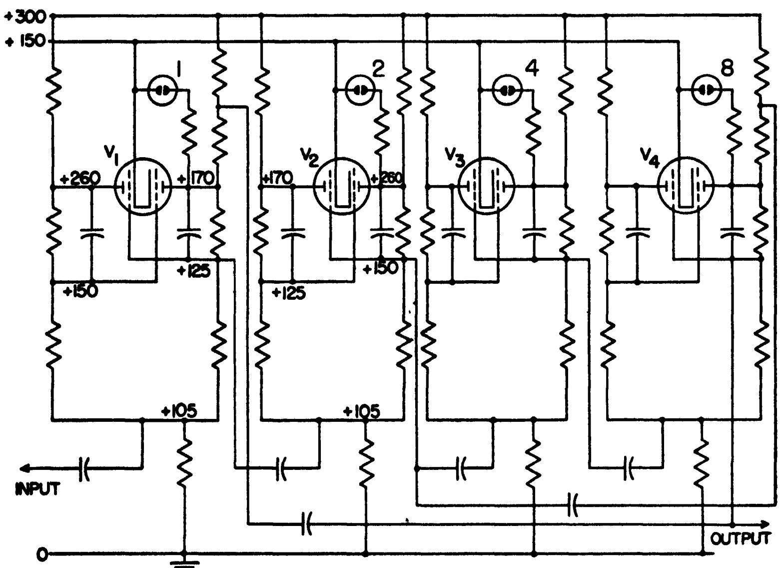


FIG. 8–3. Circuit of a single-decade counter.

In the circuit the grid of the right-hand section of V_1 is at +150 volts or zero grid bias, and, therefore, that section of the tube conducts and its anode current is large. The voltage between the anode and the cathode, however, is too low to light the neon lamp. Since the grid of the left-hand section is supplied with +125 volts, the resultant grid bias is substantially below the cutoff value, and that section does not conduct. When a pulse that makes both grids negative is applied to the input circuit, there is no effect on the left-hand section, but conduction through the right-hand section is momentarily interrupted. The reduction in anode current lowers the voltage drop across the anode resistor of that section, decreases the grid-bias voltage on the left-hand section to zero, and permits it to conduct. In the

meantime, the grid-bias voltage on the right-hand section is decreased, that section no longer conducts, and the anode-to-cathode voltage increases and lights neon lamp 1. In other words, the negative pulse has changed the respective voltages from the values shown for the digit 1 circuit to those given for the digit 2.

With the arrival of the next negative pulse, the circuit voltages revert to the previous condition, and the lamp is extinguished. At the same time, the drop in potential from +150 to +125 volts at the grid of the left-hand section of tube V_1 produces a negative pulse which is delivered to tube V_2 through a coupling capacitor. Voltages as given in the diagram show only the digit 2 lamp lighted, indicating that two pulses have occurred. On the next pulse, the lamp for digit 1 will light, producing a reading of 1 + 2. The tubes perform in tandem; both sections of each preceding tube operate for each output pulse, and its lamp lights on alternate operations. When a count of 9 is reached, lamps 1 and 8 are illuminated, but on the following operation when tube V_1 switches from left to right, a negative pulse is delivered to tube V_4 that causes its left-hand section to be biased below cutoff, makes its right-hand section conductive, and extinguishes the lamp for that tube. During the switching of tube V_4, a pulse of sufficient magnitude is fed back to tube V_2 to prevent the pulse normally arriving from tube V_1 from operating V_2. As a result, the lamp for V_2 does not light, all decade lamps are extinguished, and the final pulse is transmitted to the first tube in the succeeding tens decade, lighting the lamp for tube V_1 in that decade. Subsequent pulses again register on the first decade until the count of nine is reached, when the next pulse causes digit 2 to register on the tens decade, and so forth. One or more decades are reset, in preparation for a count, by disconnecting the +150 volts from the cathodes of all the left-hand tube sections.

Ordinarily two decades are connected in tandem, followed by an electromagnetic solenoid counter to extend the counting range. The input signal usually consists of negative pulses having an amplitude from 5 to 150 volts and a duration of about 10 microseconds, or the instrument may be energized by an a-c signal of the same range of effective voltages at frequencies from 40 to 1000 cycles per second. Instruments can be designed to

operate at much higher pulsing rates; for example, a four-decade counter chronograph, which will measure intervals up to 0.099,99 second, has been constructed to measure projectile velocities. It operates in conjunction with phototube trigger circuits and a crystal-controlled 100-kilocycle oscillator to supply the accurately timed pulses. With suitable circuit modifications and

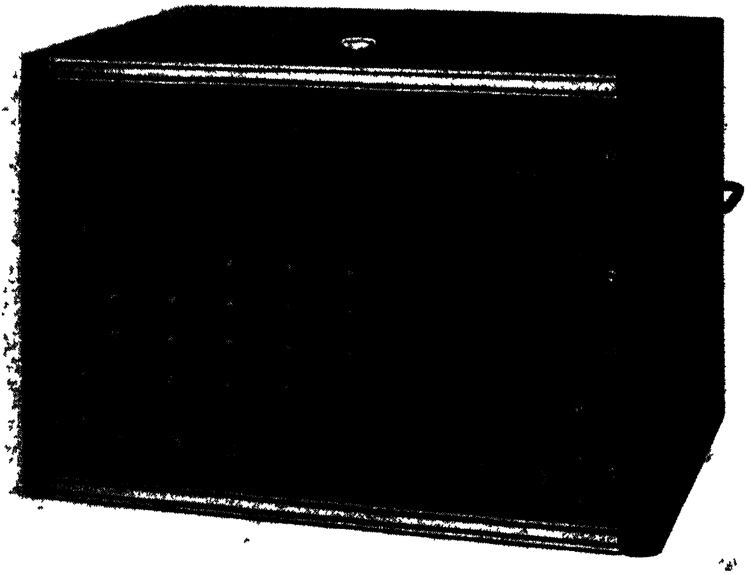


FIG. 8-4. A dual predetermined electronic counter which utilizes four decade circuits. *Courtesy Potter Instrument Company.*

the use of rotary switches, counters can also be made to deliver one or two output pulses after a predetermined count. Such an instrument, arranged for the predetermination of two different counts and providing alternate switching of the output circuit at the completion of each count, is illustrated in Fig. 8-4. It finds application in the manufacture of zippers, where the length and spacing of the fasteners can be varied quickly and conveniently, and in the counting and packaging of small articles.

Counter principles are also applied to calculators or computers, which may be divided into two classes, the digital and the analog. Ordinary adding machines and the more complicated mechanical

computers, which deal with numbers directly in digital form, are representative of the first class. The second class employs physical quantities to represent numbers: for instance, the simple slide rule, which multiplies and divides numbers by adding lengths, and the highly complex differential analyzer, which represents numbers by angular rotations of mechanical shafts. The ENIAC (Electronic Numerical Integrator and Computer),

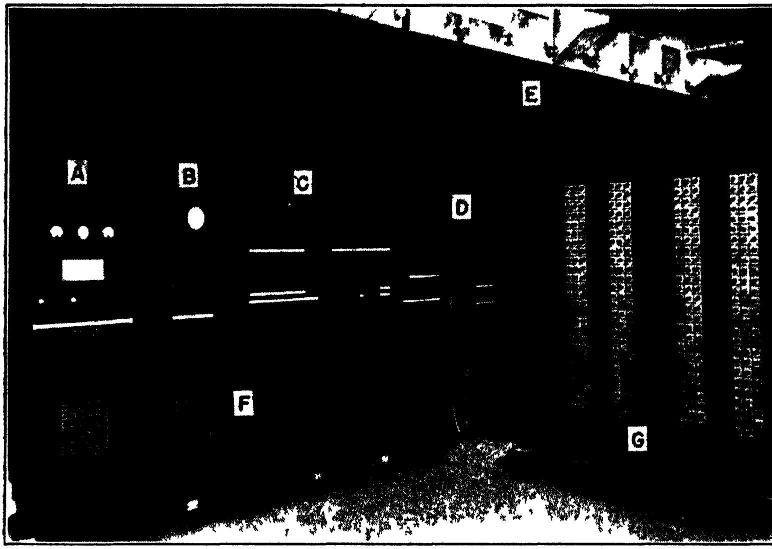


FIG 8-5 Partial view of the ENIAC showing initiating unit panel *A*, pulse generator panel *B*, master program panels *C*, function table panels *D*, accumulator panels *E*, program trays *F*, and function table *G* *Courtesy United States Army Ordnance Department.*

developed by J. W. Mauchly and J. P. Eckert and completed in 1946, is the first all-electronic calculating machine. It is of the digital type, and operates by the counting of electrical pulses produced at the rate of 100 kilocycles per second. The machine solves problems, such as those involving integration, differentiation, or the solution of simultaneous algebraic or transcendental equations, by reducing these processes to numerical computations of addition, subtraction, multiplication, division, square rooting, and obtaining values of functions. It has twenty accumulators, or panels, which add, subtract, or store (remember) numbers until required; three function tables, which also supply numbers such

as trigonometric functions; a panel that is used for division and square rooting; and several other panels where miscellaneous functions are performed to initiate operation or programming, to modify basic operational processes, and to punch or print the final result or tabulation on a card. Obviously, such a machine is extremely intricate and is mentioned here only because it represents the largest and most involved electronic device constructed previous to 1950. Figure 8–5 shows only a portion of the complete ENIAC; the entire unit is 100 feet long and 10 feet high. It contains about 18,000 tubes, many of which are twin triodes; it consumes about 80 kilowatts for filament power, and requires 40 kilowatts for the d-c power supply.

The computer has produced results of inestimable value in both theoretical and applied fields of science and engineering. Many ordnance, aerodynamic, and thermodynamic problems, formerly incapable of solution because of the tremendous amount of time and labor involved, can be solved on the machine in a matter of hours.

8–3. Metal Detectors

Whenever a conducting substance such as metal is placed in proximity to a current-carrying inductor, eddy currents are induced in the substance, causing a change and distortion of the magnetic field with a resultant change in the value of the inductance and an increase in the exciting current. In addition, if the substance is magnetic, the field is increased, depending on the permeability of the material, and the inductor current is also increased to compensate for the hysteresis loss. These effects are used in transducers for instruments designed to measure the thickness of paint and lacquer coatings on metallic surfaces and to separate physically similar, but metallurgically different, stock materials.

The minute change of inductance that occurs in tests where the object may be small or some distance from the inductor is detected quite readily by making the search coil part of the resonant circuit of one of the oscillators in a *beat-frequency oscillator*. In such a circuit two high-frequency oscillators are used; one has a fixed frequency and the other is variable. Each oscillator output is applied to one of the two control grids of a pentagrid mixer, in the output circuit of which the difference

frequency is separated, and then applied to an amplifier, rectifier, and an output meter. The variable-frequency oscillator is adjusted to have the same frequency as the fixed oscillator, and since there is no output from the mixer tube there is no meter indication. However, when the search coil approaches a metallic object, a beat-frequency signal voltage is generated and a deflection of the output meter occurs.

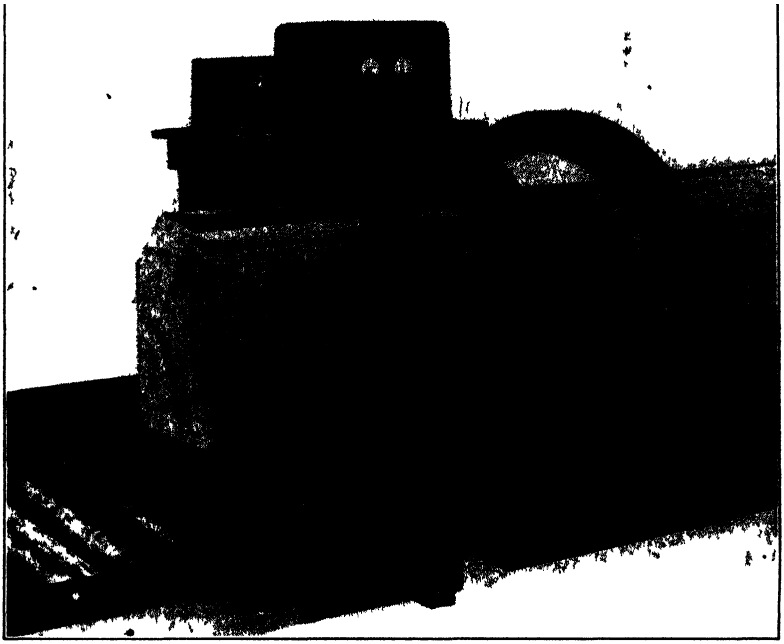


FIG 8-6. A veneer flitch tester. *Courtesy Magnaflux Corporation.*

A different type of metal detector is based on a modification of the induction balance, developed by D. E. Hughes in 1879. In its simplest form it consists of two identical air-core transformers with the two primary windings connected in series, and the two secondary windings also connected in series but with their induced voltages opposed to each other. No mutual inductance exists between the two transformers, and, consequently, a telephone receiver or meter connected across the secondary circuit gives no indication; that is, the output voltage is zero. Alternating voltages having frequencies between 60 and 1000 cycles per second are generally used to supply the primary circuit.

When a piece of metal is placed near or within one of the transformers, the induced voltages in both secondary windings are no longer equal and a measurable unbalance voltage exists across the secondary terminals.

A metal detector employing this principle is the veneer flitch tester, illustrated in Fig. 8–6. It is used to detect nails and other metallic material in woods which are to be sliced or cut

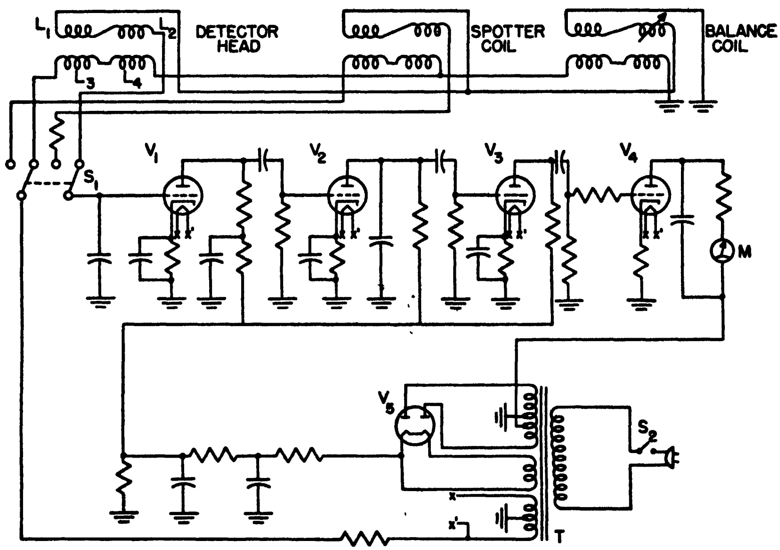


FIG. 8–7. Circuit of an electronic tire inspector. *Courtesy Magnaflux Corporation.*

into veneer. Nails driven into the trunk of a small tree will be completely imbedded in the wood as the tree grows, and they can do great damage to expensive saws or cutting knives in the manufacture of veneer. By passing these sectioned logs, termed flitches, along a conveyor, which carries them into the coils shown in the figure, any imbedded metal sets up a voltage unbalance in the pickup coils. This voltage is impressed on an amplifier, shown in the rear, and is amplified to a level to operate a relay and signal light. By observation of the meters, the imbedded metal may be located exactly and removed before the flitch passes to the knives.

The circuit of an instrument designed to detect metal objects in automobile tires is given in Fig. 8–7. Three induction balances

are shown, the detector head, the spotter coil, and a balance coil which is used to adjust the meter reading to zero before making a test. Primary windings L_3 and L_4 of each of these transformers constitute in effect a continuous winding; the secondary windings, such as L_1 and L_2, are connected so that the induced voltages oppose each other. The voltage across the secondary terminals of the balance coil may be changed in magnitude and phase by means of a very small iron screw which can be moved to either side of the center line of the coil. A switch S_1 permits either the detector head or the spotter coil to be used in series with the balance coil. As the tire is rotated, any imbedded metal particles in the tire disclose their presence on a line across the tire by an indication on the meter. The metal is then located exactly by the spotter coil.

Metal detectors reveal the presence of tramp metal particles in blocks of raw material used in the fabrication of phonograph records. These biscuits, as they are commonly called, sometimes contain metallic particles which will damage the highly delicate and intricate pressing dies. Another important adaptation of these principles is in the precise location of metal fragments in surgery, and in the testing of a-c relay coils for short-circuited turns.

8-4. Electronic Voltmeters and Potentiometers

Electromagnetic meters of the d-c type ordinarily use a D'Arsonval movement, whereas a-c types generally employ either the electrodynamometer principle or a d-c meter with a dry-plate rectifier. Although the power consumption of these meters is entirely negligible when they are used on low-resistance power circuits, the increased voltage drop caused by the meter current in high-resistance communication circuits disturbs the voltages and results in erroneous meter readings. The *vacuum-tube voltmeter* has been developed as a simple, accurate, and convenient instrument to measure direct, alternating, or both direct and alternating voltages in high-impedance circuits. Basically, all such circuits depend for their operation on the action of a diode or on the amplifying action of a suitably biased triode.

A simple circuit for a diode voltmeter consists of a rectifier tube, an ordinary indicating meter, and a current-limiting resistor in series. Since conduction takes place only during the

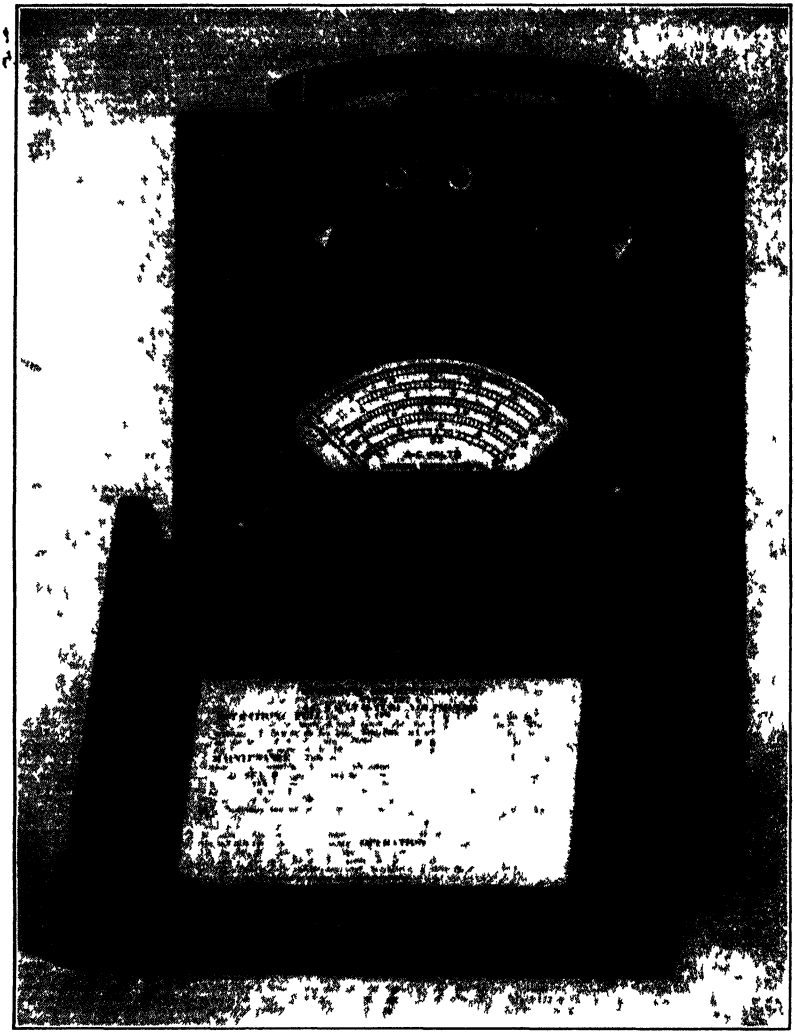


FIG. 8-8. Photograph of an a-c vacuum-tube voltmeter. *Courtesy General Radio Company*

positive half-cycle, the average current through the circuit for one cycle of a sinusoidally varying alternating voltage is

$$I_{av} = \frac{0.318E_m}{R} = \frac{0.450E}{R}, \tag{8-1}$$

where E_m is the maximum voltage, E is the effective voltage, and R is the combined circuit resistance, assumed to remain constant, of the resistor, meter, and tube. When the meter is used for direct voltage measurements, with proper regard for polarity, the current I through the meter is

$$I = \frac{E}{R}. \tag{8-2}$$

Additional advantages of the diode-type vacuum-tube voltmeter are that it can be used for measurements on frequencies higher than about 5000 cycles per second, where ordinary meters fail to perform, and for low-voltage measurements if the diode is followed by a suitable amplifier. An instrument of this kind is illustrated in Fig. 8–8, and the circuit is given in Fig. 8–9.

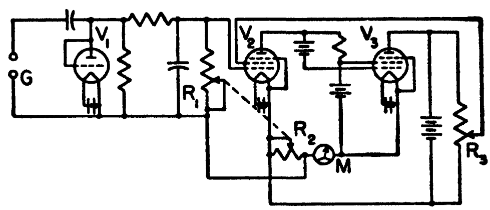


FIG. 8–9. Circuit of the a-c vacuum-tube voltmeter.

Tube V_1, a triode of the acorn type designed for high-frequency amplification and rectification, is connected as a diode. The capacitor in the input circuit prevents any direct voltage from reaching the tube and allows only the alternating component of the unknown voltage to be impressed on the voltmeter. Terminal G indicates the ground connection, which must be connected to the low-potential point of the circuit in order to obtain true readings that are free from parasitic capacitance effects. Output of the diode is impressed on an amplifier tube V_2, which has an adjustable resistor R_1 in its input circuit for multirange operation and a resistor R_2 in the cathode circuit to obtain proper grid bias. Resistor R_2 also provides inverse feedback for a wider range of impressed voltages and produces greater proportionality between meter reading and input voltage. Tube V_3 serves as an additional amplifier and with resistor R_3 offers a means for balancing out the zero-signal direct current in the meter. This instrument is designed to measure alternating volt-

ages from 0.05 volt to 300 volts in seven ranges. For sinusoidal voltages its accuracy is about 2 to 3 per cent with a frequency error of less than 1 per cent between 20 cycles and 30 megacycles. It is calibrated to read the effective value of a sinusoidal voltage; however, on higher voltage ranges it is essentially a peak-reading device calibrated to read 0.707 of the peak value of the applied voltage.

An ordinary class B amplifier affords the foundation circuit for a slide-back or comparison-type vacuum-tube voltmeter. In this type, the anode current is set to some low value by adjustment of the grid-bias voltage. After the voltage to be measured has been applied the anode current is again reduced to the original value, and the difference in the two bias readings indicates the crest value of the impressed voltage. The advantage of such a meter is that peak voltages may be read by direct comparison without output meter calibration, but the accuracy is limited because the residual reading is more or less indefinite since the anode current varies but little with large grid voltage changes near the cutoff point.

Measurement of very high voltages requires a potential divider. Resistors are frequently used to divide the voltage, or a large and a small capacitance of the air-dielectric type are connected in series across the unknown voltage, with the vacuum-tube voltmeter connected across the larger capacitance. Since voltages across two capacitors in series divide inversely as their capacitances, the voltage drop can be made quite small by using a large capacitance ratio.

Under ordinary conditions a current of 10^{-6} to 10^{-8} ampere flows in a negatively biased grid circuit of a vacuum tube. It flows because of a positive-ion current, caused by the ionization of residual gas molecules, because electrons from the cathode strike the grid, and because of electrical leakage. Special tubes, such as the FP-54 triode, have been designed to reduce these factors to a minimum. These tubes have exceedingly high-input impedances and in suitable circuits are able to detect currents as low as 10^{-17} ampere. They are applied to measure the hydrogen-ion content of chemical solutions or the ion current in the mass spectrometer, and are used as substitutes for electrometers.

Electronic potentiometers offer a means for continuous measuring and recording of extremely low direct voltages. Cyclically

operated galvanometer balancing mechanisms used in connection with continuous mechanical motion reached a high degree of perfection in the potentiometer-type pyrometer. However, such factors as galvanometer inertia, pivot friction, and sensitivity can be reduced only to certain minimum values, irrespective of cost, and, consequently, designers have developed improved electronic instruments that eliminate a number of these factors, increase the sensitivity, and provide continuous balance. The schematic diagram, Fig. 8–10, of an electronic potentiometer pyrometer is

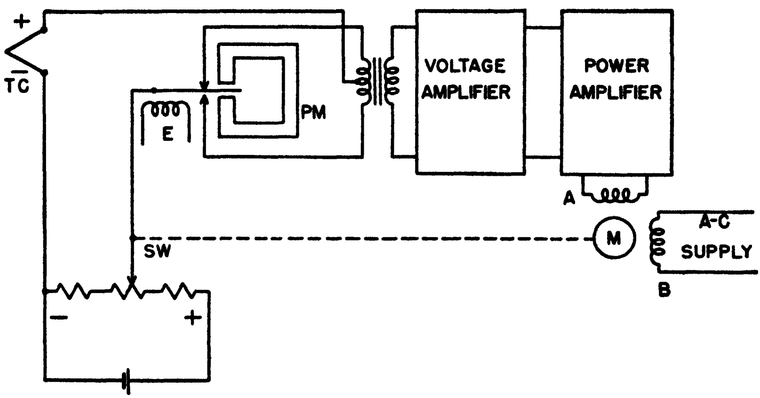


FIG. 8–10. Simplified schematic diagram of a continuous-balance electronic potentiometer pyrometer. *Courtesy Brown Instrument Company.*

composed of five parts: the measuring circuit, a converter, a voltage and power amplifier, a rectifier power supply, and the balancing motor.

The measuring circuit comprises the thermocouple *TC* and a slide wire *SW* through which a known current flows. Adjustment of the slide wire arm is made by means of the motor *M* to balance the thermocouple voltage; the motor, in turn, is actuated to rotate in the proper direction by the polarity of the unbalanced voltage impressed on the amplifier. The converter is of the vibrating-reed permanent-magnet type, energized by an alternating voltage impressed on coil *E* so that the reed vibrates in synchronism with the power-supply frequency. Contacts on the reed connect the unbalanced voltage to either side of a center-tapped input transformer; they produce a control voltage that alternates at the power frequency and that is either in phase or 180° out of phase with the a-c power supply.

The three-stage voltage amplifier is resistance-capacitance-coupled, but the power amplifier, as shown in the simplified schematic diagram of Fig. 8–11, is designed to be phase-selective. Two tubes are used; their grids are connected in parallel. The anodes are supplied with alternating voltage from the center-tapped secondary winding of transformer T. Polarity is assumed to be as indicated in the diagram for positive half-cycles of the a-c supply voltage; it is reversed for negative half-cycles. Tube V_1 can conduct only during the positive half-cycles, and tube V_2 can conduct only during the negative half-cycles. There

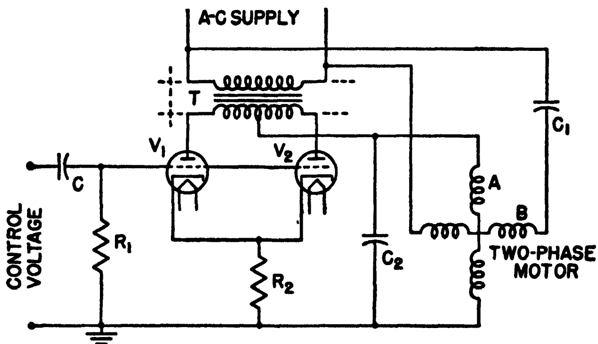


FIG. 8–11. Phase-selective power amplifier used in the electronic potentiometer pyrometer.

is, therefore, a definite phase relationship between the control voltage, derived from the thermocouple circuit, and the output of the power amplifier.

The balancing motor is of the two-phase induction type; its direction of rotation is reversed by interchanging the connections of one phase winding or reversing the current through it. Phase winding B, connected in series with capacitor C_1, is energized from the a-c supply voltage. Phase winding A, with capacitor C_2 connected in parallel, derives its energization from the power amplifier. With the polarity, as indicated in the figure, and with the proper grid potential, tube V_1 conducts; a current pulse flows through winding A; and capacitor C_2 is charged during the positive half-cycle. During the succeeding negative half-cycle the grid potential is displaced by 180°, due to the converter, tube V_2 cannot conduct even though its anode is positive, and

capacitor C_2 discharges through the winding. In this instance the motor rotates in a specific direction and restores the slide-wire contactor to the position where no unbalance exists between the slide wire and thermocouple voltages. If an opposite-polarity unbalanced voltage exists, the control voltage causes tube V_2 to conduct and the motor rotates in the opposite direction until balance is restored. After this no voltage is applied to the grids of the power tubes, and both act as rectifiers; they apply pulsat-

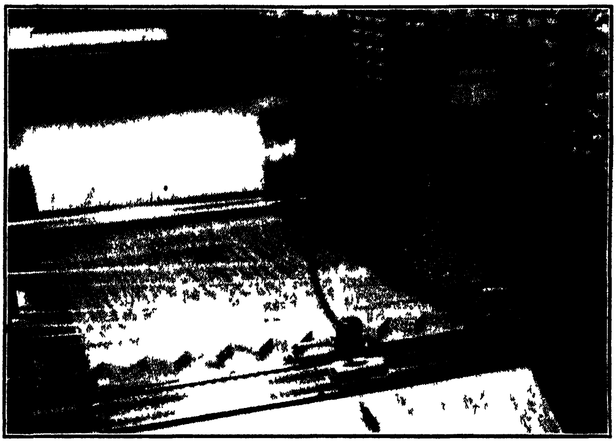


FIG. 8–12. Textile mill installation of a Moist-O-Graph, a device that determines the moisture content in tentered cloth. *Courtesy Brown Instrument Company.*

ing direct current to the motor winding *A* which causes a braking action and prevents travel past the null position. An instrument pointer attached to the slider arm provides a visual indication of the temperature in addition to the printed or graphic record. Instruments of this kind indicate an unbalance in the thermocouple circuit as low as 50 microvolts.

By replacing the thermocouple with a suitable pickup, which generates an electromotive force or across which a variable voltage drop occurs in proportion to the variation of the quantity under observation, various process variables, such as *p*H, mechanical strain, and rotative speeds, can be measured and recorded. A typical installation of an electronic recording potentiometer is shown in Fig. 8–12.

8-5. Comparators and Surface Analyzers

Precision of manufacture is determined by gauges; the dimensions of a piece part must be held to given tolerances if interchangeability, the prime requirement of mass production, is to be met. So long as the tolerances are measured only to 0.001 inch, mechanical devices and amplifying systems are generally satisfactory. However, when precise measurements must be made to 0.000,01 inch, electronic gauges supply the required need.

Electronic comparator gauges use a pickup that operates on the principle of displacing an armature, which may be mounted

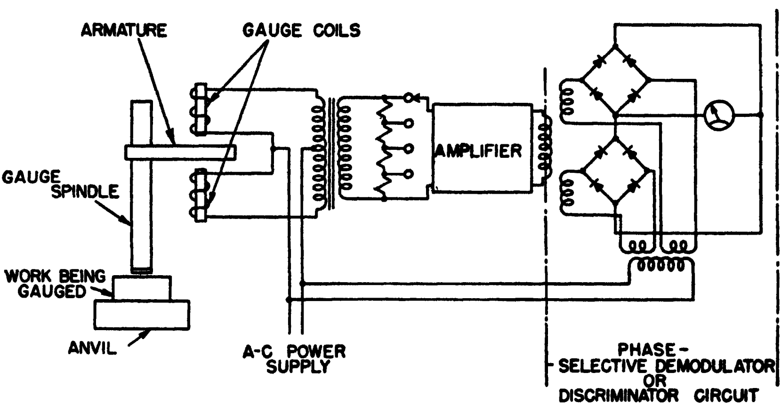


FIG. 8-13. Simplified schematic diagram of an electronic comparator gauge. *Courtesy Hathaway Instrument Company.*

directly on a spindle, to generate a corresponding voltage. As shown in the schematic diagram of Fig. 8-13, the armature is normally in a central position between two small coils wound on iron cores. Any change in the position of the armature modifies the magnetic field and results in a change in the electrical balance between the coils. This unbalance manifests itself as an alternating voltage in the secondary winding of the transformer, and it is either in phase or 180° out of phase with the supply voltage depending on the transformer connections and on the displacement of the armature from the central position. According to the setting of the instrument range switch, a portion of the secondary voltage or all of it is amplified and delivered to a phase-selective demodulator or rectifier circuit whose output

causes a deflection of the zero-center d-c meter. The meter is calibrated in appropriate units, and the displacement of the armature from its neutral position indicates on the meter the extent of the deviation from the nominal dimension, either plus or minus, of the piece part being measured.

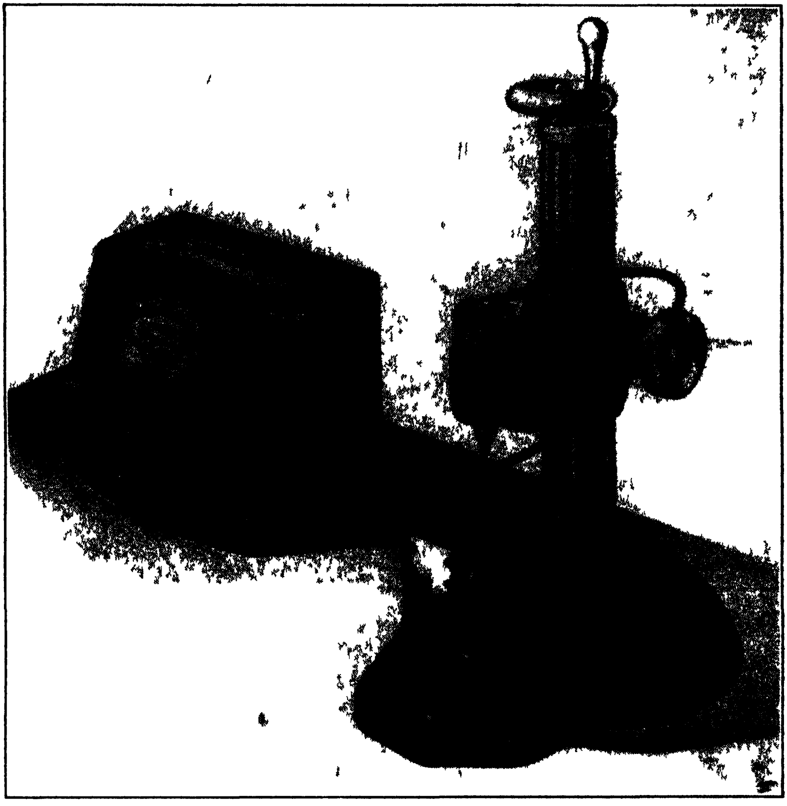


FIG. 8–14. Photograph of an electronic comparator and height gauge. *Courtesy Jack & Heintz.*

Limit gauges take various forms for different inspection jobs. Figure 8–14 shows a typical external comparator. Aircraft engine parts for selective assembly need to be classified rapidly into precise groups, and for such inspection the distance from the anvil to the spindle is set accurately by means of high-precision gauge blocks, so that the exact deviation from the nominal size of the work is indicated on the meter. The mating parts are

similarly inspected and classified with an internal comparator, and in the final assembly the use of corresponding groups insures a perfect fit. The specific gauge illustrated in the figure is arranged with two scales to indicate 0.000,01 and 0.000,1 inch per division. In the ball-bearing sorter illustrated in Fig. 8–15 steel balls are fed from a hopper, one at a time, across an anvil and under the arm of the gauging head, the impulse from which



FIG. 8–15. An electronic ball-bearing separator. *Courtesy Jack & Heintz.*

energizes one of ten solenoids through the electronic system. From the gauging head, the ball runs down an inclined track, and the energized solenoid diverts it into the proper one of ten containers. If its diameter is outside the range for which the machine is set, it is rejected into an eleventh container. The balls are automatically sorted into ten groups with a measurement tolerance of as little as plus or minus 0 000,005 inch, depending upon the sensitivity setting. Sorting of this type is achieved with laboratory precision at production-line speed and costs.

Recurrent or random surface irregularities on a smoothly machined surface generally have amplitudes from about 1 to 250 microinches and repeat these amplitudes between 0.010 and 0.030 inch. High mechanical precision, demanded in certain automo-

tive and airplane parts, requires other methods than a visual or a fingernail test if quantitative data are to be obtained. Furthermore, the development of superfinishes and improvements in precision finishing machines have made possible the machining of such parts as bearing surfaces that are too smooth, so that the seizing tendency after assembly is greatly increased. Surface roughness on blueprints is generally specified as the root-mean-square height of the roughness in microinches and may be deter-

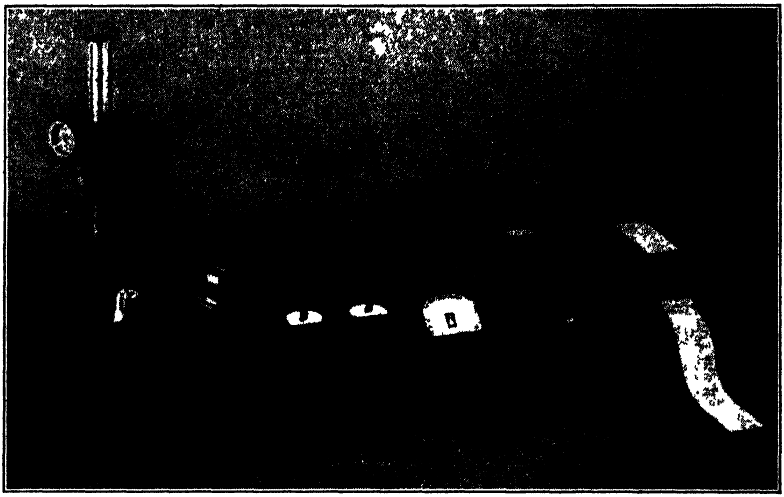
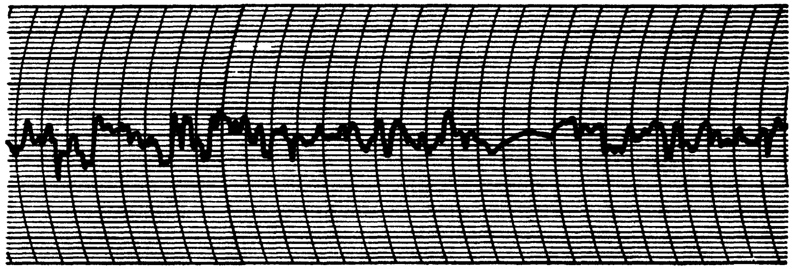


FIG. 8–16. Surface analyzer consisting of a crystal-type transducer, amplifier, and magnetic recorder. *Courtesy Brush Development Company.*

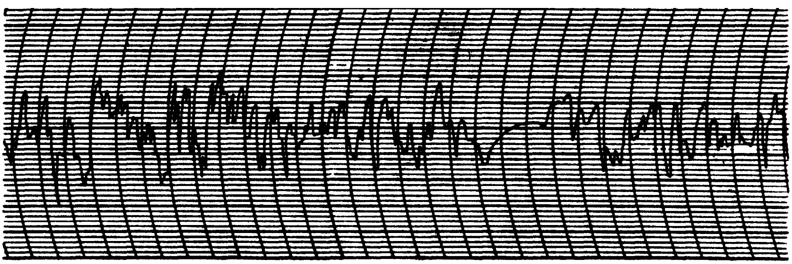
mined by a profile meter or surface analyzer, one form of which is illustrated in Fig. 8–16. The instrument consists of three major components: an analyzer head, an amplifier, and a recording oscillograph.

The analyzer head carries a sharp exploring stylus attached to a piezoelectric Rochelle-salt crystal element and arranged with a synchronous motor drive so that the stylus moves with a reciprocating motion along the specimen at the rate of 0.0125 inch per second. The diamond stylus point has a tip radius of 500 microinches for the measurement of ordinary surfaces; a stylus radius of 100 microinches is used for superfinish measurements. Mechanical damage to the tracer point is avoided by the use of a member, equipped with a shoe positioned to ride over a

relatively large area of the specimen; the shoe acts as a reference level for the tracer point. The crystal, made with either two or four rectangular wafers, has over-all dimensions of 1½ inches by ⅜ inch by 0.030 inch. It is supported at one end, and the tracer point is mounted at the other. As the stylus moves along the



(*a*)



(*b*)

FIG. 8–17. Typical surface records taken on the same surface with the electronic surface analyzer. (*a*) Scale 10 microinches; (*b*) scale 5 microinches. *Courtesy Brush Development Company.*

specimen, any vertical motion caused by surface irregularities will bend or stress the crystal, and a voltage will be generated between its ends. The two-ply crystal element, used with the smaller stylus, has a sensitivity of 1.8 millivolts per microinch of vertical deflection.

The three-stage resistance-capacitance-coupled amplifier actuates a direct-inking electromagnetic oscillograph; it has a voltage magnification of approximately 2000 and delivers a maximum output of 22 volts to the recorder. Variations in surface finishes from less than 1 microinch to 5000 microinches may be readily determined with the small stylus. Two profile charts, taken at different scales and shown in Fig. 8–17, show the high degree of

reproducibility of the data. Normal chart speed is 1 inch per second, which is equivalent to an 80-to-1 horizontal magnification. In addition to the oscillograph, an indicating meter provides a visual check of surface roughness and may also be used where profile charts are not required.

8–6. Engine and Detonation Indicators

Pressure-volume indicator diagrams of reciprocating steam engines indicate changes in pressure within the cylinder and the timing of the various valves, and provide an index of engine per-

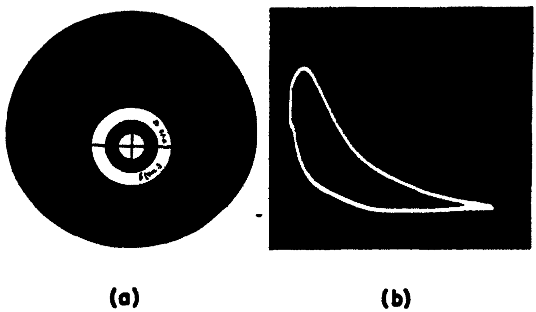


FIG. 8–18. (*a*) Facsimile of a disc used with a phototube to obtain a horizontal volume-sweep for recording indicator diagrams on an oscilloscope. (*b*) Typical indicator diagram. *Courtesy Armour Research Foundation.*

formance and efficiency. An analysis of a diagram discloses whether the expansion and compression were adiabatic or isothermal and also tells at what point between these limits the machine functioned. With the newer compressors and high-speed engines, the problem of obtaining indicator diagrams becomes much more involved, since the mechanical inertia of an ordinary engine indicator prevents the proper recording of the rapidly recurring changes. A solution to the problem consists in the utilization of a suitable pickup that supplies a varying voltage in conformity with pressure variation and that may be amplified and impressed on the vertical deflection plates of a standard oscilloscope. A volume-sweep generator producing a voltage varying in direct proportion to the piston displacement is required, in addition to the pressure component, to complete an engine-indicator diagram. In one form this is obtained by having the light from a steady light source, falling on a phototube

through an optical slit, periodically changed in intensity by an eccentrically rotating opaque disc. The disc is designed so that it alternately covers and uncovers the optical slit, thus varying the quantity of light falling on the phototube in direct proportion to the varying volume of the engine-cylinder chamber. The



(a)

FIG. 8–19. (a) Normal flame growth within a gasoline-engine cylinder. (b) Flame growth during detonation. *Courtesy Sperry Gyroscope Company.*

shaft supporting this disc is directly coupled to the crankshaft of the engine and turns at the same speed. The phototube is connected to a separate amplifier that impresses its output on the horizontal deflecting plates of the oscilloscope. This device furnishes the volume component of the engine-indicator diagram. A facsimile of a rotating disc, and a typical indicator diagram, with the volume plotted as abscissas and the pressure as ordinates, are given in Fig. 8–18.

During operation the phase relationship of the two amplifiers is properly adjusted, and the scale of each of the two components of the resultant indicator diagram is adjusted to the desired value

by modifying the gain of each amplifier. In fact, with sufficient amplification any small portion of the pressure-volume diagram may be enlarged and examined in detail by adjusting the centering and amplifier controls on the oscilloscope. Instantaneous changes, and changes caused by various adjustments of the mechanical parts of the engine while in operation, are readily

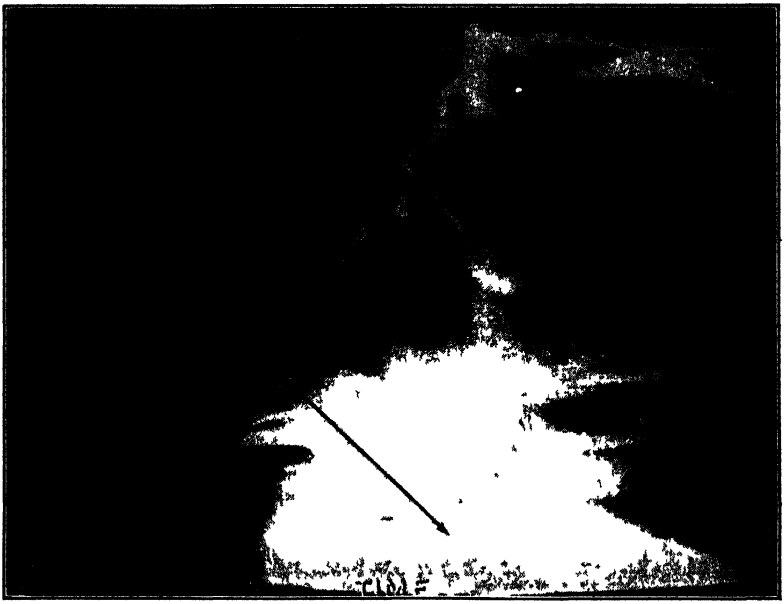


FIG. 8–19 (*b*).

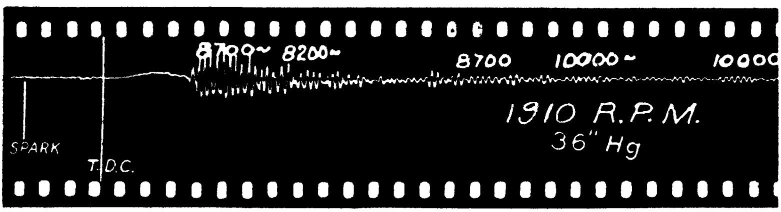
observed. Photographing the trace through a transparent rectangular-coordinate index grid, suitably marked and fastened over the screen of the cathode-ray tube, yields a negative that can be analyzed directly.

Internal-combustion engine operators have long been harassed by the problem of detonation. As fuel efficiency and compression ratios are increased, the demand for direct detection and immediate evaluation of detonation becomes more and more acute, particularly in connection with aircraft operation and in research work on high-octane fuels. An indication of detonation in its early stages enables the pilot to adjust the fuel-air ratio of the engine for safe operation and to maintain an economical mixture under the continuously changing conditions encountered in flight.

It reduces the possibility of engine failure from detonation and at the same time permits a substantial saving in fuel, a longer engine life, and reduction of engine maintenance. In fuel-rating tests, a detonation indicator discloses the precise point at which engine efficiency becomes impaired and has proved itself extremely useful in the development of new and more efficient engine fuels. As may be seen from Fig. 8–19(*a*), progressive flame growth



(*a*)



(*b*)

FIG. 8–20. Oscillograms of vibrations in a gasoline engine. (*a*) Normal operating condition; (*b*) detonating condition. *Courtesy Sperry Gyroscope Company.*

within the cylinder takes place uniformly and without any abrupt changes after ignition occurs. However, during detonation, Fig. 8–19(*b*), there is an extremely rapid rise in pressure and in the cylinder-head temperature within the combustion chamber, and audible pressure waves are produced. Vibrations that accompany normal combustion and engine operation are illustrated in Fig. 8–20(*a*); the characteristic vibrations that result from detonation are shown in the companion oscillogram, Fig. 8–20(*b*). When detonation occurs, the vibrations repeat from one to five times per minute and almost once for every cycle for the more severe conditions.

One of the instruments used for determining detonation or for rating the detonation qualities of fuel is known as a Knockmeter.

It consists of a vibration pickup attached to the exterior of the cylinder head; a commutator, which selects only the pickup output voltage caused by combustion vibrations; and an amplifier, equipped with a suitable output meter and a neon-lamp indicator. The pickup, adapted to a fuel-rating engine and shown in



Fig. 8–21. Photograph showing pickup and commutator of a Knockmeter installation on a fuel-rating engine. *Courtesy Sperry Gyroscope Company.*

Fig. 8–21, operates on the magnetostrictive principle, whereby physical deformations change the reluctance of a magnetic circuit and cause an induced voltage in a coil wound over a permanent magnet. The pickup is mounted on a boss on the cylinder, since it is neither necessary nor desirable to pierce the combustion chamber in order to obtain a record of the engine vibration. A commutator closes the pickup circuit only during the combustion period; this eliminates the vibration transients that are produced when the intake and exhaust valves strike their seats. The

pickup voltage, which is of the order of a few millivolts, is impressed on an adjustable amplifier or preferably on one equipped with automatic volume control. This control is required in some installations because the vibration amplitude during detonation is proportional to the amplitude of the normal combustion vibra-

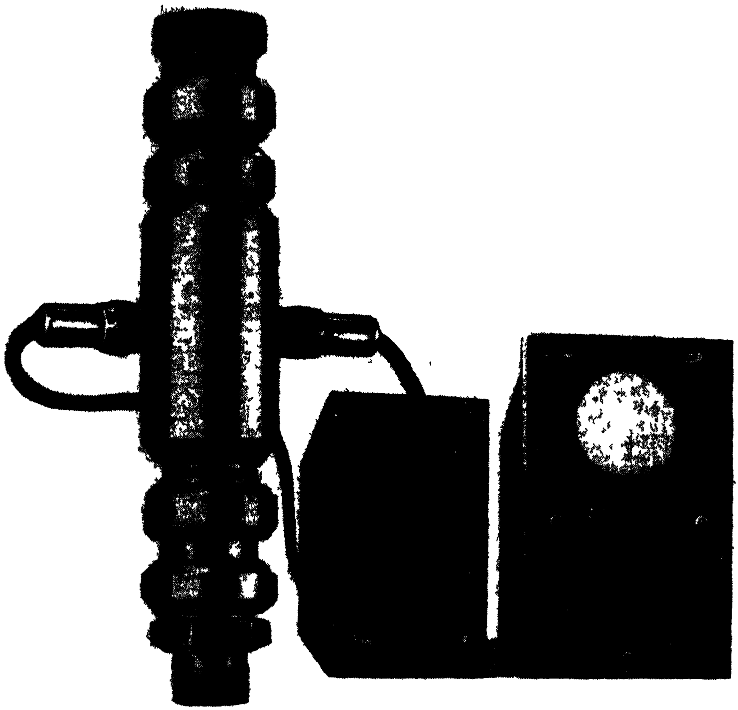


FIG 8–22 The Pressuregraph, a pressure-indicating system that utilizes a capacitor-type pickup, an amplifier, and an oscilloscope *Courtesy Electro Products Laboratories.*

tion, which, in turn, varies with changes in engine conditions. At low power the amplitude of detonation vibrations is several times that of combustion vibrations, whereas at high power the amplitudes of both are correspondingly increased. If a fixed-gain amplifier were used, any adjustment made at high power would make the instrument appear insensitive when the engine is operated at low power, because a large detonation would be required to operate the visual indicator. On the other hand, if

the amplifier were adjusted for low power the indicator would appear too sensitive at high power, so that it would give a false indication of detonation. The knock-discriminating circuit terminates in a suitable output meter that provides relative readings for laboratory work, while the flash of a small neon lamp acts as an indicator for detonation in aircraft and other engine installations.

Investigations and studies can be made of the pressure-time relationships in compressors, injection pumps, and the like, and a

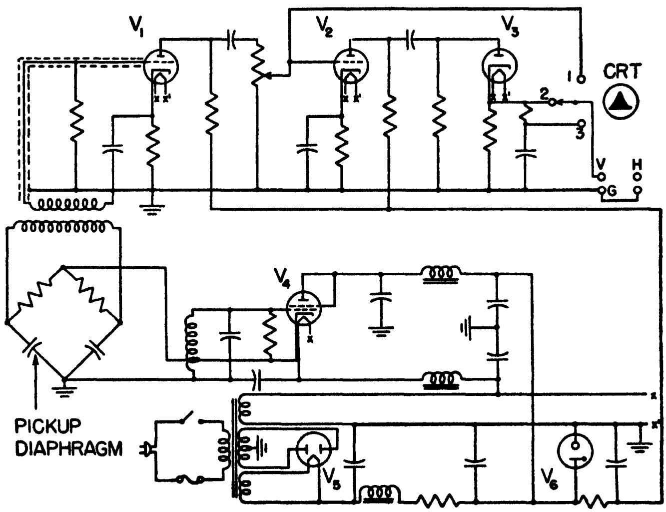


FIG. 8–23. Circuit diagram of the Pressuregraph.

visual indication of the normal and detonation pressures in a gasoline engine cylinder can be obtained from the instrument illustrated in Fig. 8–22. It consists of a pickup, an amplifier-integrator-oscillator combination, a cathode-ray oscilloscope, and a synchronizing device that provides a steady locked-in trace on the screen. The pickup is of the capacitor type, containing a thin diaphragm spaced from a solid backing electrode, and is connected in a bridge circuit as shown in Fig. 8–23. A 100-kilocycle-per-second alternating voltage, derived from the oscillator tube V_4, is supplied to the bridge. Any unbalanced voltage from the bridge is delivered to the input of the amplifier tube V_1. Its output may be directed to the oscilloscope through the switch contact 1 or through an additional amplifier stage V_2 and a recti-

fier V_3 through switch contact 2. With the latter setting, the oscilloscope trace for a pressure stroke is as indicated in the figure. If the switch is set on contact 3, the output delivered to a capacitor totalizes the voltage variations and produces a trace proportional to the integrated pressure, that is, to the amount of engine knock when used as a detonation indicator. Tube V_5 is connected as a conventional full-wave rectifier and supplies the required d-c voltages, stabilized by the voltage-regulator tube V_6.

8-7. Strain Gauges and Vibration Meters

Static quantities, such as weight, pressure, or draw-bar pull, are obtained easily with ordinary instruments, particularly in the laboratory, but dynamic measurements, made under actual field conditions, are not so readily secured. However, mechanical, civil, and aeronautical engineers and designers need accurate information on what load each structural member can bear; large safety factors that are not required utilize excess material and introduce unnecessary weight and cost. This search for more definite knowledge led to the development of strain gauges.

Most strain gauges consist of either a grid or a flat helix, composed of fine alloy wire about 0.001 inch in diameter mounted on a paper base by means of a suitable elastic cement. The gauges are made in various sizes with lengths from $\frac{1}{8}$ inch to $1\frac{1}{16}$ inches and with resistance values ranging between 120 and 500 ohms, but with the resistance value of each gauge accurately adjusted during manufacture to the value called for by the specific type. The gauges are mounted to the surface of the member under observation by means of a cellulose nitrate or Bakelite cement and are usually connected in a temperature-compensated bridge circuit that terminates in an amplifier equipped with a meter or recording oscillograph.

When the structural member is placed under stress, the wire in the strain gauge changes in length and cross section, and the resistance R changes in accordance with the equation

$$R = \frac{\rho L}{A}, \qquad (8\text{-}3)$$

where ρ is the specific resistivity of the material of which the strain gauge wire is made, and L is the length and A is the area of the wire.

The gauge sensitivity factor K_s is defined as the ratio of unit change in resistance to unit strain causing the change, or

$$K_s = \frac{\Delta R/R}{\Delta L/L}, \tag{8-4}$$

where ΔR and ΔL are the incremental changes in gauge resistance and length of the specimen respectively, and R and L are the original values. Gauge factors vary between 1.8 and 3.5; for some still unexplained reason their values are slightly higher than those calculated by Eq. 8–3. The temperature coefficient of a gauge while in use is in general larger than that of the alloy wire because of the temperature coefficient of the structural member on which the gauge is mounted; for accurate readings, temperature compensation is made by using a similar, auxiliary gauge arranged so as to be free from stress but subject to the same temperature conditions in a bridge-type exploring circuit. Small direct or low-frequency alternating voltages are used to prevent temperature and corresponding resistance changes.

A simplified diagram of a bridge-type strain gauge, supplied with d-c excitation, is shown in Fig. 8–24. The operative strain gauge is indicated as R_1 and the temperature compensation gauge as R_2. Resistors R_5, R_6, and R_7 are used to balance the bridge; resistors R_8 and R_9 are used for attenuation and damping. In a typical installation the two gauges are attached to the adjacent sides of a main gear strut or axle of an airplane landing gear to obtain data regarding the stresses to which these members may be subjected during landing and to observe and compute the drag load versus time. A sample record, redrawn from one obtained on an oscillograph and showing the bending strains encountered during landing, is illustrated in Fig. 8–25. This general method of determining stress and strain can also be applied to static and dynamic loading of buildings, bridges, dams,

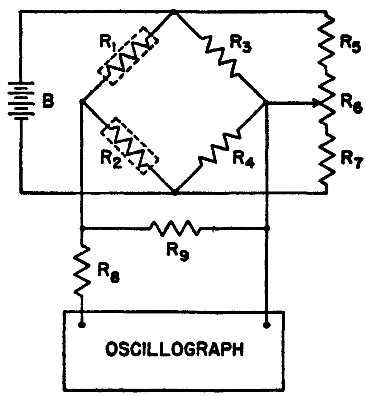


FIG. 8–24. Simplified circuit of a strain gauge.

and other structures; frequently strain gauges are placed in position during construction and used for periodic tests after the structure is completed. Strain gauges are also designed to operate on other principles than the change of resistance of a wire grid. Figure 8–26 illustrates the application of magnetic-type strain gauges to a machine to keep a constant check on its loading.

Sound and vibration are usually considered as interrelated and different aspects of the same phenomena. But in a narrower

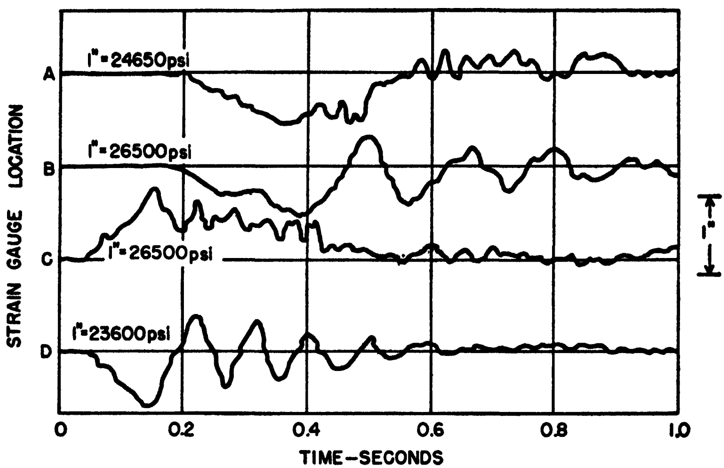


Fig. 8–25. Copy of a record of the bending strains encountered in various portions of an airplane landing gear during landing. *Courtesy United States Army Air Forces.*

sense, we consider sound and noise as pressure variations that take place in air at audible frequencies and vibration as the mechanical movements that occur within solids. Of course, vibrations give rise to sound, although important low vibration frequencies of the order of only a few cycles per second are commonly encountered. Rotating machinery, office typewriters, automobiles, printing presses, and pneumatic drills not only frequently produce unnecessary noise and vibrations, which reflect themselves in human annoyance, deafness, and nervous disorders, but also cause the machines to vibrate themselves to pieces. Quiet machines are usually associated with well-balanced construction. Moreover, specifications are often set up for maximum allowable machine noise which manufacturers must meet.

There is no doubt that noise reduction in a plant or office increases efficiency, reduces error, decreases absences, and reduces employee turnover. In a number of controlled experiments of this nature the last three factors were decreased from 30 to 50 per cent. An over-all noise reduction of even 10 decibels yielded very tangible and noticeable results.

Various forms of sound-level and vibration meters have been developed for commercial and industrial noise measurement. The one illustrated in Fig. 8–27 consists of a nondirectional

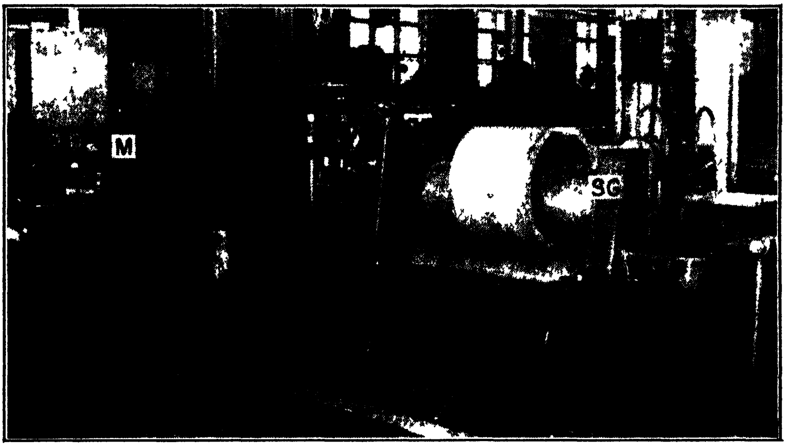


Fig. 8–26. Bending roll provided with strain gauge equipment. Instruments over controller at *M* show per cent of rated loading during rolling operations. *Courtesy General Electric Company.*

microphone or a vibration pickup, an amplifier, a calibrated attenuator, and an indicating meter. The pickup is of the inertia type which delivers a voltage proportional to the acceleration of the vibratory motion. It is constructed with a piezoelectric crystal fastened firmly to the pickup housing at three corners, and during operation the inertia of the crystal causes it to bend when the housing is vibrated.

Vibration, like other motions, can be measured in terms of displacement, velocity, and acceleration. In a simple sinusoidal vibratory motion, the instantaneous displacement s can be written as

$$s = A \sin 2\pi ft, \qquad (8\text{–}5)$$

where A is the amplitude, f is the frequency, and t is the time. Of course, the crest-to-crest displacement is $2A$, and the root-mean-square value is $0.707A$. Displacement measurements

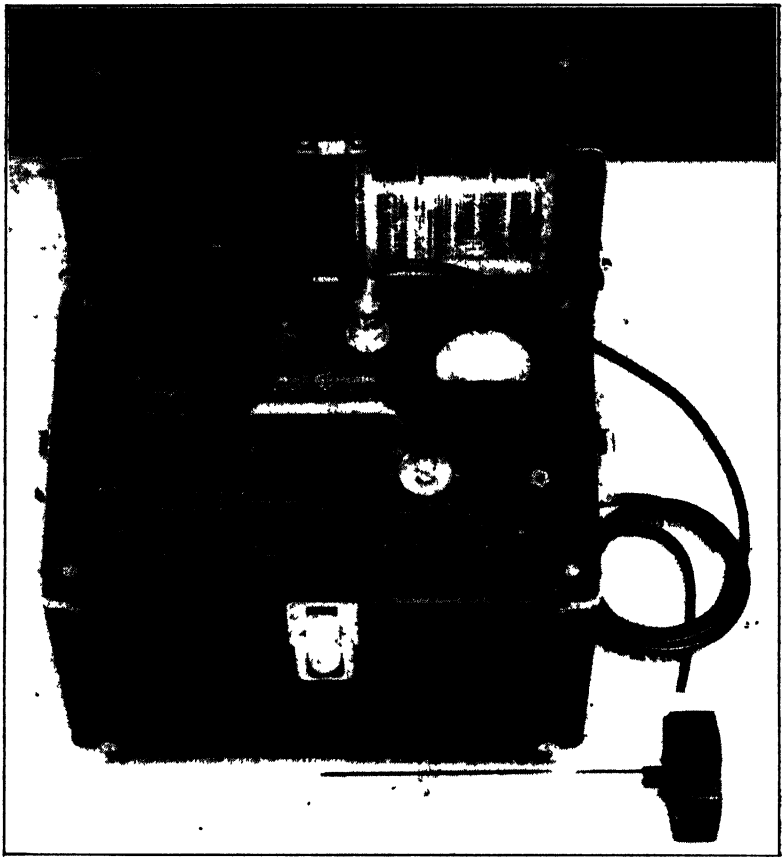


Fig. 8-27. Vibration meter, designed particularly for machinery vibration problems, covers the frequency range from 2 to 1000 cycles per second. *Courtesy General Radio Company.*

provide an indication of total movement irrespective of frequency.

Velocity, the time rate of displacement, is obtained by taking the first derivative of Eq. 8-5, or

$$v = \frac{ds}{dt} = 2\pi f A \cos 2\pi f t. \tag{8-6}$$

It will be noted that the velocity is proportional not only to the displacement but also to the frequency of the vibration. Velocity of a vibration is also proportional to vibration energy and permits the measurement of the noise produced by a vibrating surface.

Acceleration, the time rate of velocity or the second derivative of displacement, is written

$$a = \frac{dv}{dt} = \frac{d^2s}{dt^2} = -4\pi^2 f^2 A \sin 2\pi ft. \tag{8–7}$$

This shows that acceleration is proportional to the displacement and to the square of the frequency; it is also proportional to the resultant force produced by the vibration. Measurements of this kind are important in the determination of high-frequency vibrations, in problems where mechanical failure of the parts is in question, and in most noise determinations. A vibration meter, therefore, should be capable of measuring all three vibration characteristics. In the instrument shown in Fig. 8–27 any type of response, as desired, may be selected by means of pushbutton switches, and acceleration, velocity, and displacement of a vibrating body may be measured independently. Since the pickup responds to the acceleration of the vibratory motion, integrating networks convert its output, when desired, into readings proportional to velocity or displacement.

A simple integrating circuit, Fig. 8–28(*a*), consists of a resistor and capacitor in series connected across the input; the output is connected across the capacitor. A simple differentiating circuit, Fig. 8–28(*b*), uses the same circuit elements but they are interchanged. According to Kirchhoff's voltage law, the input voltage e_1 in either case is

$$e_1 = Ri + \frac{1}{C}\int i\,dt. \tag{8–8}$$

For an integrating circuit, the value of R is made large so that $Ri > 1/C\int i\,dt$, and Eq. 8–8 becomes

$$e_1 \approx Ri, \tag{8–9}$$

and

$$i \approx \frac{e_1}{R}. \tag{8–10}$$

The voltage across C, that is, the output voltage e_2, is

$$e_2 = \frac{1}{C}\int i\,dt, \tag{8–11}$$

and

$$e_2 \approx \frac{1}{RC}\int e_1\,dt. \tag{8–12}$$

In other words, the output voltage is proportional to the integral of the input voltage.

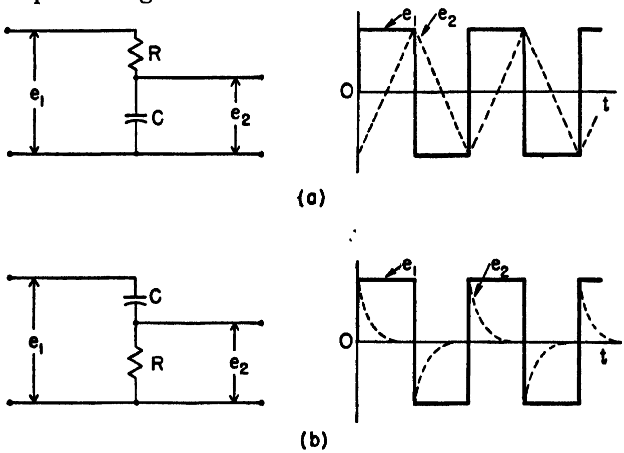


FIG. 8–28. (*a*) A simple integrating circuit. (*b*) A simple differentiating circuit. Waveforms of input and output voltages are given to the right of each circuit.

The differentiating circuit, Fig. 8–28 (*b*), requires that Ri be small compared to $1/C\int i\,dt$. Therefore,

$$e_1 \approx \frac{1}{C}\int i\,dt, \tag{8–13}$$

and

$$i \approx C\frac{de_1}{dt}. \tag{8–14}$$

The voltage drop across R, that is, the output voltage e_2, is

$$e_2 = Ri \approx RC\frac{de_1}{dt}, \tag{8–15}$$

or, the output voltage is proportional to the derivative of the input voltage. Figures adjacent to the circuit show the waveforms obtained when a square-waveform voltage is impressed on each circuit.

Vibration meters are calibrated to read displacements in microinches, velocity in microinches per second, and acceleration in inches per second per second. Meter indications are read directly



FIG. 8–29. A sugar cane-grinding tandem consisting of three engines driving a set of revolving knives, a 2-roll crusher, and seven 3-roll 78-inch mills. *Courtesy United States Sugar Corporation.*

in root-mean-square values; an attenuator changes the meter scale; and additional multipliers indicate the correct units of measurement and provide multiplying factors for each response characteristic. If the waveform under observation is not sinusoidal, a frequency analyzer, which measures the amplitude of each individual frequency component, is connected to the output circuit of a sound-level or vibration meter. A simple frequency analyzer consists of (1) a high-gain amplifier with a frequency-selective feedback network designed so that the feedback is degenerative at all frequencies except the one to which the network is tuned, and (2) an indicating instrument consisting of a logarithmically calibrated vacuum-tube voltmeter. During use the

loudest component of sound, or the greatest reading in vibration measurements, is adjusted to give a reading of 100, that is, an equivalence of zero decibels, on the vacuum-tube voltmeter, after which the amplitude of other frequency components is indicated directly in decibels or in percentage as the frequency-adjusting dial is rotated.

Applicability of a vibration analyzer can perhaps best be illustrated by the solution of a specific vibration problem. In the production of sugar at the sugar house, shown in Fig. 8–29, the

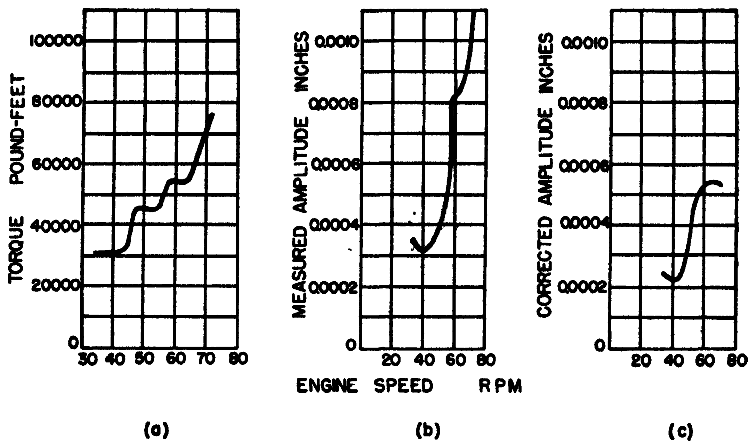


FIG. 8–30. Compound amplitudes at engine No. 2 of the grinding tandem as measured on the concrete foundation with a vibration meter. *Courtesy General Radio Experimenter.*

cane is cut up by whirling curved knives of the shredders and then is crushed between two large grooved rolls. These exert a pressure of over 350 tons, causing 60 per cent of the juice to be extracted. After this operation, indicated at the far left in the figure, the cane moves into a series of three grinding mills where the remainder of the juice is removed. An examination disclosed that the concrete foundation, about 145 feet long, 40 feet wide, and 11 feet thick for over one-half its width, was vibrating badly and that the amount of vibration increased with the load and with the speed of the center or No. 2 engine. This 36-inch by 60-inch Corliss engine operates at 40 to 70 revolutions per minute, depending on the amount of sugar cane being crushed and on its fiber content. The foundation is located on the typical

muck-on-sand-on-porous-rock of the Florida Everglades, where the water level is about 3 feet below the surface; it carries a safe, well-distributed load of about 0.8 ton per square foot. With a vibration meter and analyzer the response characteristic of the foundation, as shown in Fig. 8–30, indicated that a definite resonance peak for a constant vibrating force existed at a frequency which corresponded to an engine speed of about 68 revolutions per minute, that the prominent vibration frequency was identical with the frequency of the gear mesh of the main pinion on engine No. 2, and that other vibration frequencies were multiples of this frequency. Subsequent measurements disclosed that the driving pinion was in poor alignment with the two large gears and that the pinion teeth and the two gears were worn and were causing the vibration.

8–8. Electronic Chronometers

The speed of rotation of the earth on its axis, a factor which has been found to vary only a few hundredths of a second in a century, is checked every clear night by the United States Naval Observatory, where the 24-hour interval between the successive overhead passing of a star is observed to an accuracy within 1 part in 30,000,000. This gives us star or sidereal time, our absolute time standard. Accurate time designation and interval measurement as we know them today started when C. Huygens in 1657 introduced the pendulum into a clock mechanism. A clock pendulum or a balance wheel with its escapement in a watch gives us a measure of its oscillation by controlling the motion of the hands on a dial to indicate time.

Very elaborate and accurate pendulum clocks have been devised as standards, but their accuracy was greatly exceeded by a clock devised and built by W. A. Marrison in 1927 which depends for its operation on a crystal-controlled vacuum-tube oscillator. This clock had a daily deviation of less than 1 part in 1,000,000 and was subsequently improved so that the daily deviation was 1 part in 10,000,000. Today crystal-controlled oscillator-type clocks can be built in a greatly simplified form, notwithstanding the fact that their accuracy has been further improved to the point where the daily deviation is well under 1 part in 100,000,000. They are extremely stable in operation, free from the effects of gravity, and have an accuracy much greater

than even the most precise pendulum clock; they find application in navigation, seismology, photograph transmissions by radio, and geological surveys.

A highly accurate clock, developed by the National Bureau of Standards, is utilized to broadcast second time pulses throughout

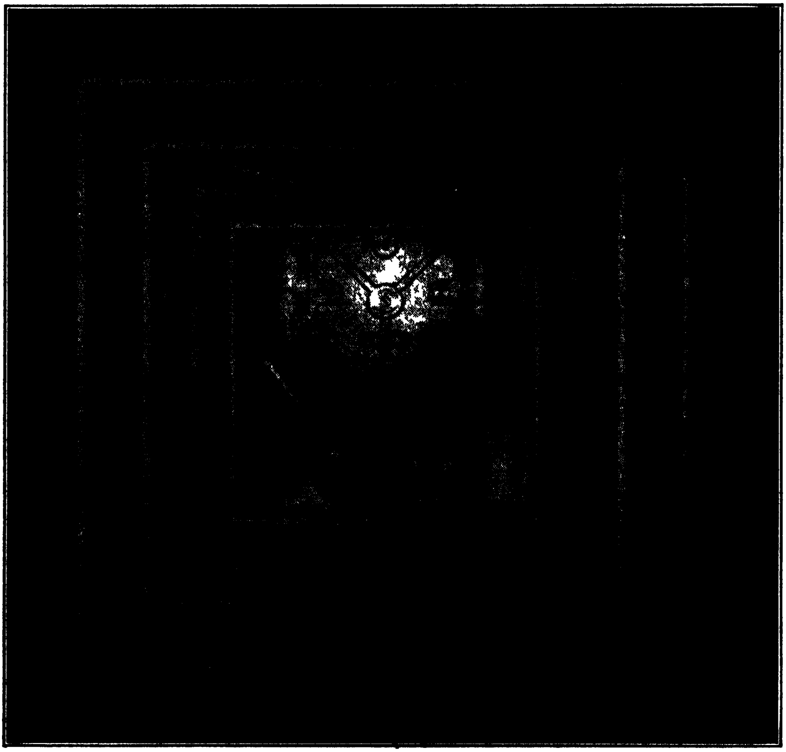


FIG. 8–31. Interior view of the 100-kilocycle standard-frequency oscillator that controls time signals. *Courtesy National Bureau of Standards.*

the world. They are broadcast continuously day and night on two or more frequencies of 2.5, 5, 10, 15, 20, 25, 30, and 35 megacycles per second and may be received on an ordinary short-wave receiver. A crystal-controlled electron-tube oscillator, basically the same as that shown in Fig. 3–29, generates an alternating voltage at a frequency of 100 kilocycles per second. Temperature, atmospheric pressure, and humidity exert an influence on the periodicity of the quartz crystal plate; to eliminate these effects

the plate is sealed in a glass enclosure and mounted with other components of the oscillator circuit in a constant-temperature oven, as illustrated in Fig. 8–31.

Frequency-dividing circuits produce a frequency of 60 cycles per second with no loss in accuracy. This low-frequency power is supplied to a synchronous motor that, through gear trains,



FIG. 8–32. Rear view of the seconds-pulse generator and interval selector used in the time-control equipment of radio station WWV. *Courtesy National Bureau of Standards.*

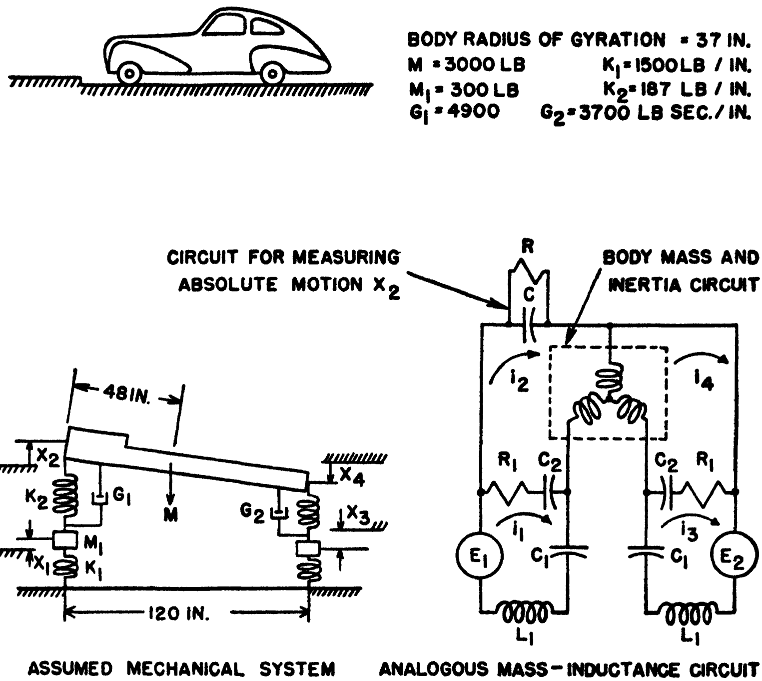
drives contacts to give intervals of 1 minute, 5 minutes, and 30 minutes to control the automatic announcement equipment of the eight transmitters. The motor also operates a 1-second contact that opens an electrical gate and allows a highly accurate seconds pulse to be broadcast. Figure 8–32 shows the seconds pulse generator and the interval selector. A cam on the flywheel, next to the synchronous motor, opens the gate for the broadcasting of the seconds pulses; the longer intervals are controlled by succeeding cams.

Even though the absolute accuracy of the crystal-controlled oscillator frequency is within a few parts in 100,000,000, phase shifts and other factors limit the accuracy to 1 part in 1,000,000. Consequently, the length of a 1-second interval, as broadcast, is accurate to 1 microsecond while the interval of 1 minute or longer is accurate to a few parts in 100,000,000. These standard time signals are coordinated closely with the United States Naval Observatory's time signals and are, therefore, also based on sidereal time. In addition to transmitting these highly accurate time intervals, the signal also provides standard radio frequencies; a continuous audio frequency of 440 cycles per second, which is the musical note of *A* about middle *C;* and another superimposed audio frequency of 4000 cycles per second. Warning notices of radio propagation disturbances are broadcast in code at stipulated periods on the same radio frequencies.

8–9. Analogue Computers and Analyzers

In electrical analogue-type computers, units of inductance, capacitance, and resistance are appropriately connected to represent the physical elements of a problem in mechanics, hydraulics, or thermodynamics. Physical forces are represented by voltages or currents, applied at proper points and arranged in amplitude and time variation to simulate conditions as they exist in the problem under investigation. The resulting output is reproduced on a suitable measuring instrument, such as a vacuum-tube voltmeter, potentiometer, or cathode-ray oscilloscope. Thus, for displacement in a mechanical system, mass may be represented by inductance, a spring constant by the reciprocal of capacitance, friction or velocity damping by resistance, force by a voltage, and displacement by a current. For torsional vibration analysis, the inertia of a shaft may be represented by inductance, the torsional stiffness by the reciprocal of capacitance, the damping constant by resistance, the torque by a voltage, and the angular velocity of torsional vibration by a current. By interchanging inductance and capacitance, as well as voltage and current, an alternate system of electrical equivalents is developed with a mass-capacitance instead of a mass-inductance analogy. One form of analogue computer is known as a mechanical transients analyzer. It utilizes amplifiers, oscillators, integrators, differentiators, and other electronic equipment.

The transients analyzer has been used to determine the motion of the wheels and body of an automobile as it passes over a stepped surface in the roadway. This application combines translational and rotational motion and considers the combination of mass and rotational inertia constants as represented in



(*a*)

FIG. 8–33. Determination of the ridability of an automobile. (*a*) Physical system and its electrical analogue; (*b*) oscilloscope traces of wheel and body motions as the car goes over a bump. *Courtesy Westinghouse Electric Corporation.*

one plane. Constants of the car and the equivalent circuit for measuring the various motions are given in Fig. 8–33(*a*). When the mass-inductance analogy is used, the effect of a stepped surface is introduced into the circuit by a suddenly applied constant voltage E_1, which is proportional to the upward displacement of the bottom of the front tires. Another voltage E_2, simulating the sudden displacement of the bottom of the rear tires, is then applied 0.45 second later, which is equivalent to a car speed of

15 miles per hour. Currents i_1 and i_3 are the analogous velocities of the wheels, while currents i_2 and i_4 are the analogous velocities of the two ends of the body. Voltages across capacitor C_1 indicate the proportional displacement of the wheels, whereas those

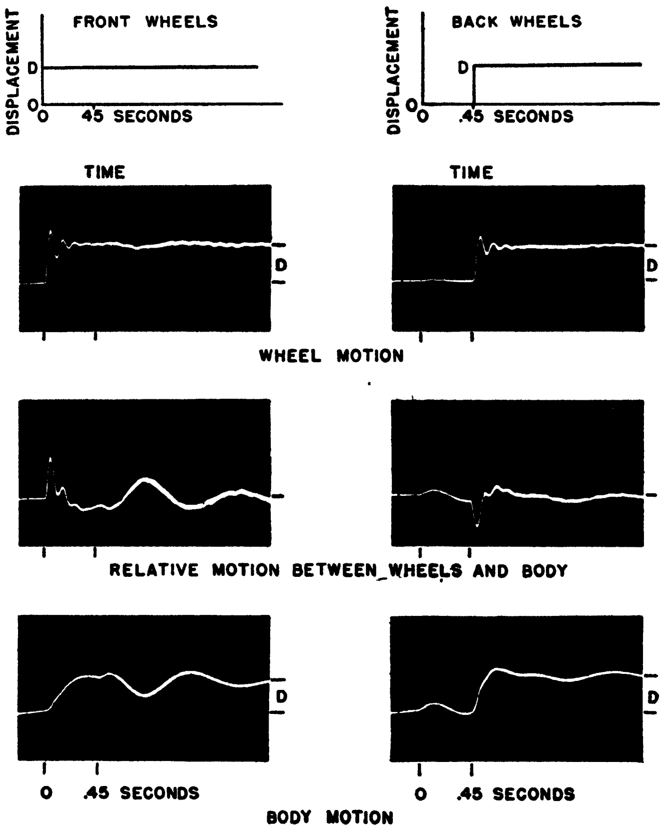
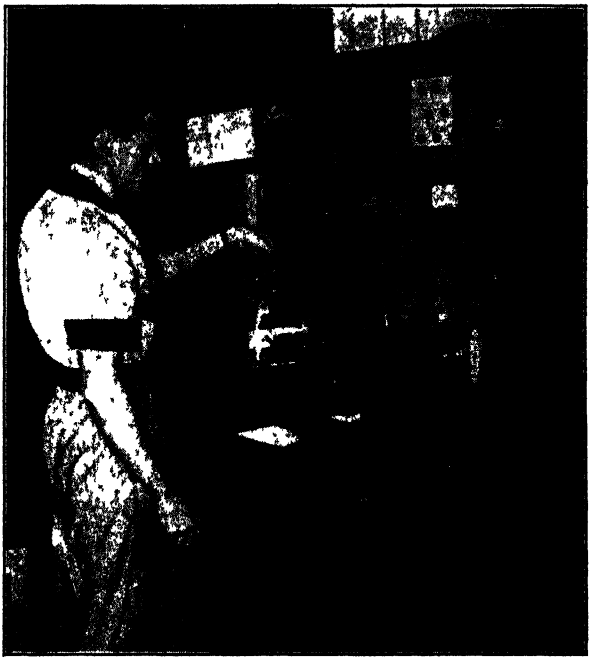


Fig. 8-33 (b).

across C_2 indicate the relative displacement between the wheels and the body; they are shown in the oscillograms, Fig. 8-33(b). In this analogy, displacement is proportional to charge, and this, in turn, is proportional to the voltage across a capacitor. Consequently, a capacitor large enough so that it does not appreciably affect the current in the circuit may be inserted to measure the absolute motion of the body. In the figure capacitor C and resistor R represent a circuit modification to measure the absolute

motion of the front end of the car. It is evident that the transients analyzer provides a means for analyzing quantitatively a wide variety of automobile designs as to their ridability and the effect of various road surfaces on their motion. Of course, this is only one of the many analyses that can be made with this instrument.



(a)

FIG. 8–34. (*a*) Front view of an electronic test stand used to test airplane-engine governors under conditions that simulate actual flight. (*b*) Rear view of the test stand. *Courtesy Woodward Governor Company.*

Special analyzers have been designed to solve specific problems. The test stand, shown in Fig. 8–34, was designed and built for the purpose of simulating the response characteristics of an aircraft engine and a specific hydraulically actuated propeller. To accomplish this, it was necessary to devise means for reproducing torque variations of the engine with throttle setting and speed, torque variations of the propeller with speed and blade angle, operating characteristics of the propeller actuating mechanism;

and the equivalent inertia of the engine-propeller combination. All these had to be adjustable over such ranges that various engine-propeller combinations and their characteristics under various flight conditions could be simulated. When the governor is mounted on the front panel to control the stand, previously

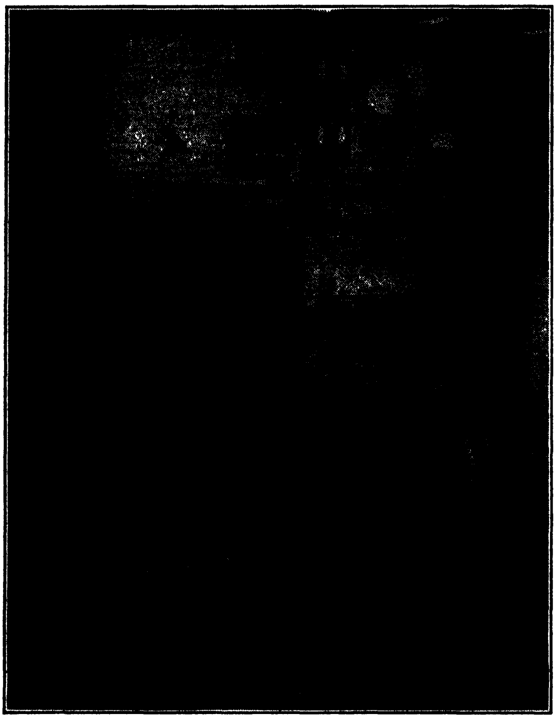


Fig. 8–34 (*b*).

set for the desired flight condition, the performance in actual service is very closely approximated.

The oil-pool analyzer, a still different analogue computer, was designed to make long-range predictions of the flow of crude oil from oil pools located at depths that sometimes exceed 3 miles beneath the surface of the earth and to act as an aid to greater and efficient recovery of the oil. Mathematical methods of predicting reservoir behavior have two shortcomings: they require a large amount of highly skilled mathematical work, and problems frequently arise which have such complex boundary

conditions that only very approximate solutions can be obtained. The analyzer, illustrated in Fig. 8–35, is based on (1) the analogy between the conductivity of an electrical conductor and the conductivity of porous media; and (2) the ability of porous media to store fluid by virtue of the compressibility of the fluid and the

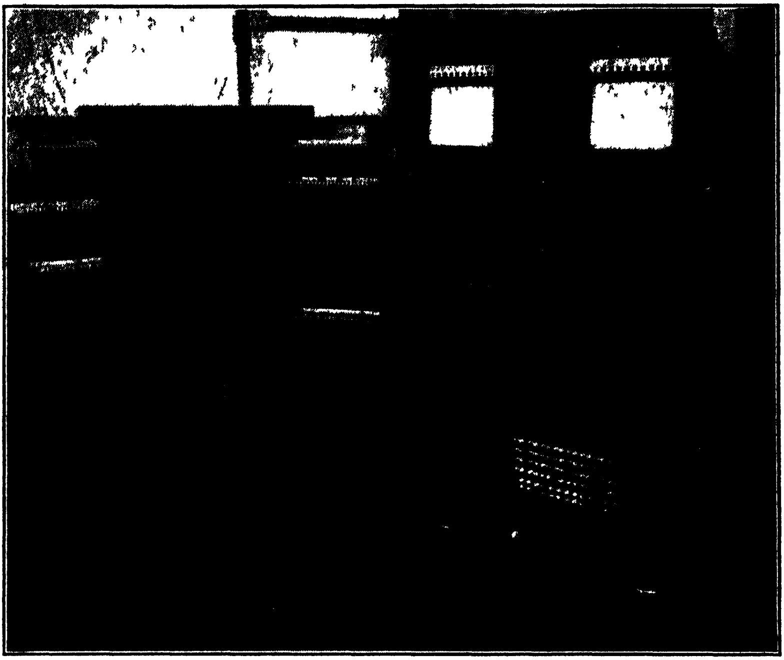


FIG. 8–35. The two principal units of the Carter oil-pool analyzer. The smaller unit is the automatic production controller; the larger contains the recorders, main controls, and the capacitors which represent stored oil and water. *Courtesy Standard Oil Company (N. J.).*

ability of a capacitor to store an electrical charge. It utilizes a network of capacitors and resistors connected together on a panel by means of cables and plugs to represent the complex conditions of the oil pool. Oil withdrawal and the effects of water drive, which result from the movement of water into an oil reservoir because of the pressure of underground water adjacent to the oil layer and which serve to force oil to the well in the absence of natural gas pressure, are simulated by adjustable amplifiers that decrease or increase the charge on the capacitors in the network.

If the fluid is water and the aquifer has a normal elasticity, a withdrawal of 10 to 15 barrels per acre-foot of aquifer causes a reduction of pressure of about 1000 pounds per square inch. Oils have higher elasticities, and if gas is involved the pressure drop is much less. The source of energy to move the water into the oil reservoir is derived from the expansion of the water in the aquifer and from the deformation of the aquifer itself. In some circumstances, injection wells, to which water or gas is pumped, maintain pressure for the oil flow. Each active well and each

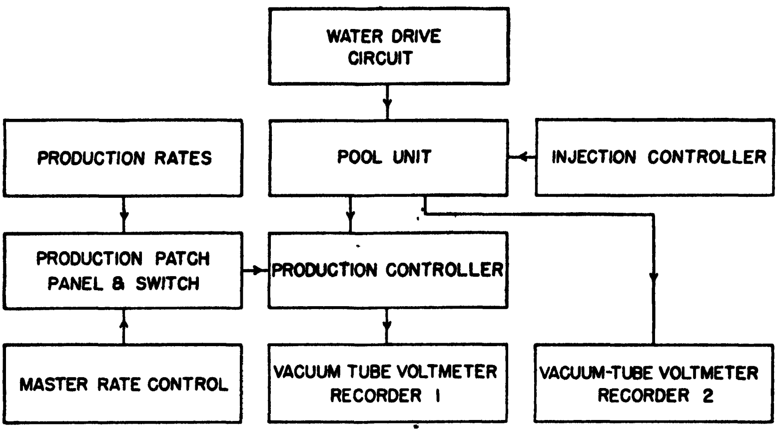


FIG. 8–36. Block-type diagram of the major components of the oil-pool analyzer.

injection well of the oil pool under investigation is represented by an electrode suitably connected to the resistor-capacitor network. A timing element, adjustable and variable, is used to fix the monthly adjustment of production or injection rates; it permits one month's history or prediction to be condensed into $2\frac{1}{2}$ seconds. At a uniform rate a 10-year analysis can be made in 5 minutes. The block-type diagram of Fig. 8–36 shows the major components of the analyzer. The underground pressure of oil and water is measured by recording capacitor voltages, and the flow of oil and water is measured by recording current flow.

This analyzer has justified its accuracy in two ways. It has taken previous data of old oil fields and predicted their behavior, exactly as they actually worked out, and has verified analyses and predictions of oil flow of new fields. As an illustration of

this, the Midway, Arkansas, pool by April 1943 had 40 wells producing 175 barrels per day, and the pressure was falling at the rate of 0.5 pound per square inch per day. It was necessary to determine the rate of production in order to arrest the pressure decline and to ascertain how much daily water injection would be necessary to maintain pressure and the same production by water injection on the flanks of the pool. An analysis was made, shown graphically in Fig. 8–37, from which it was decided to

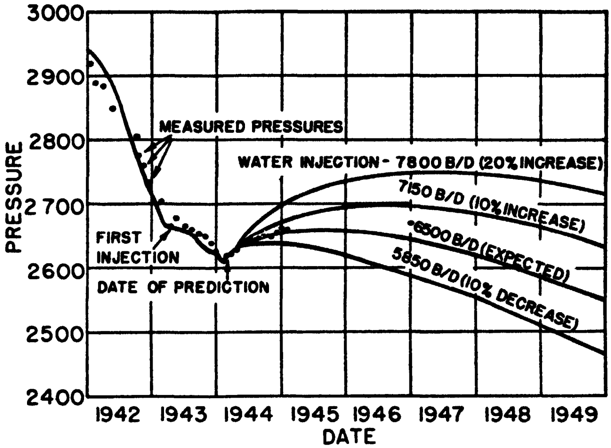


FIG. 8–37. Pressure predictions for the Midway pool in Arkansas, based on a constant oil-production rate and various indicated rates of water injection into the four injection wells. *Courtesy Standard Oil Company (N. J.).*

inject 6500 barrels of water per day to maintain the desired production. At the beginning of 1945, increased demands caused the injection rate to be increased, with the result that the pressure at the beginning of 1947 was 2670 pounds per square inch. This analysis indicated the advantage of water injection in oil pools for holding pressures and gave a striking confirmation to oil-flow determinations based on an electronic analogue computer.

8–10. Electronic Chemical Instruments

Many chemical processes involve changes in color or light transmission, and for these processes photoelectric equipment offers advantages over visual determinations by providing more exact and quantitative data. A phototube, arranged with color filters and connected in a simple photoelectric circuit, generally

suffices for ordinary color measurements of a solution during chemical analysis. For industrial control or regulator systems, a balanced bridge-type circuit employing two phototubes has definite advantages, since one of the tubes may be energized by light transmitted through a standard sample while the other receives light that passes through the sample under test. Photoelectric apparatus has been devised for a great number of diversified uses, such as automatic titration, measurement and control of chlorine added to water for purification in municipal water plants, regulation of the hardness of boiler water in power plants, hydrogen-ion determinations, and the quantitative estimation of hemoglobin in blood samples.

Many chemical and bacteriological processes depend on close and accurate control of the hydrogen-ion concentration of the solution. The symbol pH is defined as the negative logarithm of the concentration of the hydrogen ions in gram equivalents per liter. Pure water is ionized, and by experimentation it has been determined that at 22° C there are 0.000,000,1 gram equivalents of hydrogen ions and 0.000,000,1 gram equivalents of hydroxyl ions present. These are designated as $[H^+]$ and $[H^-]$ respectively, where the brackets symbolize concentration. The dissociation constant of water K_w has a value of 10^{-14} at 22° C when the concentrations are expressed as above, and

$$K_w = [H^+] \cdot [OH^-] = 10^{-14}. \qquad (8\text{–}16)$$

Both ion concentrations are equal in pure water. Consequently,

$$[H^+] = [OH^-] = 10^{-7}. \qquad (8\text{–}17)$$

Since fractional, decimal, or negative exponential expressions are inconvenient and cumbersome, the pH designation was devised to utilize the exponent only without the negative sign. Thus, pure water with a hydrogen-ion concentration of 10^{-7} gram equivalents per liter is said to have a pH of 7 or a neutral value at 22° C. The pH scale ranges from 0 to 14, where a pH of 0 corresponds to an acid solution and a pH of 14 corresponds to a basic solution, each of unit strength. The scale is a logarithmic function of concentration, and a change of one pH unit represents a tenfold change in concentration. A solution with a pH of 5 is ten times more acid than a solution with a pH of 6, and a base of 9 is ten times more alkaline than a solution

with a *p*H of 8. Control of hydrogen-ion concentration is of particular significance in operations involving neutralization, in precipitation where physical properties and grain size are affected, in coagulation where emulsions agglomerate at definite *p*H values, and in the electrodeposition of metals where the efficiency and the finish of the plating differ greatly with small variations of the hydrogen-ion concentrations of the plating solution. Some chemical processes depend on holding a solution to within a few hundredths of the specified *p*H value.

The *p*H value of a solution may be determined by measuring the voltage difference between two half-cells, one a reference electrode and the other an electrode responsive to hydrogen ions. Of the various kinds of reference electrodes, the saturated calomel type, composed of mercury and mercurous chloride with a saturated potassium chloride electrolyte, is most commonly used. A liquid junction between the electrode and the solution under test is established by means of a small hole in the housing. There are four major types of electrodes sensitive to hydrogen ions: the hydrogen, the quinhydrone, the antimony, and the glass electrodes; each has its particular advantages and limitations. The fundamental standard is the hydrogen electrode, consisting of platinum coated with platinum black, which is immersed in a solution saturated with hydrogen gas. The coating absorbs hydrogen from the solution and acts precisely as a hydrogen electrode except that the electrode is a conductor. Difference of potential developed between the standard electrode and the solution is a measure of the hydrogen-ion or hydroxyl-ion concentration of the solution. A saturated calomel reference electrode is positive with respect to the normal hydrogen electrode and at 0 *p*H its single potential varies from +0.2534 volt at 15° C to +0.2344 volt at 40° C.

Although laboratory checks are made with various types of electrodes, the glass electrode is preferred for ordinary routine laboratory determinations and for most industrial applications. It consists essentially of a thin-walled bulb on a tube of special glass, which is filled with a solution of constant *p*H value and provided with a suitable terminal electrode. The thin glass membrane separates the standard solution from the one under test, and a potential, which is a function of the two solution concentrations, is produced across the membrane. Voltage output of

any *p*H electrode varies with temperature as well as *p*H, and present-day instruments compensate for this. Exclusive of any asymmetry-potential correction, the electrode potential versus *p*H relationship of a typical glass electrode for an electrode system which has zero output at 7 *p*H is given by the equation

$$e = 0.001{,}983{,}22T\ (p\mathrm{H} - 7), \tag{8-18}$$

where e is the electrode potential in volts and T is the absolute temperature. Clearly, for the measurement of voltages involving

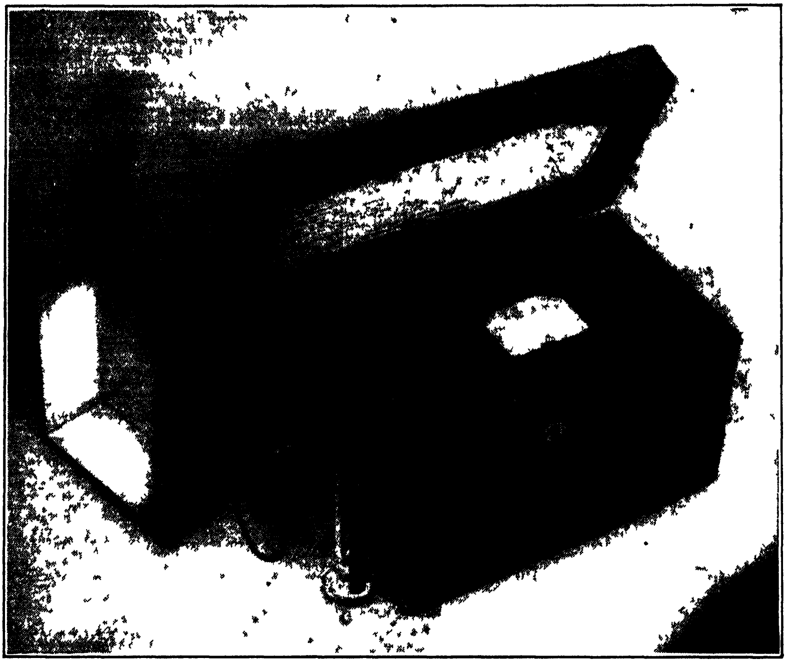


FIG. 8-38 Portable battery-operated glass-electrode *p*H indicator. *Courtesy Leeds & Northrup Company.*

a fractional part of a millivolt, precision potentiometric methods, using a standard cell as the ultimate reference, are indicated. Since the electrical resistance of the membrane of a glass electrode is extremely high, only a small amount of energy is available for galvanometer deflections, and an amplifier is used to obtain an impedance match between the high-resistance glass electrode and the low-resistance galvanometer in order to obtain satisfactory deflections of the galvanometer.

A portable battery-operated pH indicator assembly is illustrated in Fig. 8-38, and a simplified circuit of the instrument is given in Fig. 8-39. The indicator utilizes a glass electrode with a standard reference electrode and covers the range of 0 to 14 pH in two overlapping ranges of 8 to 0 and 6 to 14 pH, selected by the position of the multiple switch, S_2, S_3, S_4, and S_5. With switch S_1 in the position shown, the meter is set to zero by adjusting the coarse and fine potentiometers P_2 and P_3. After

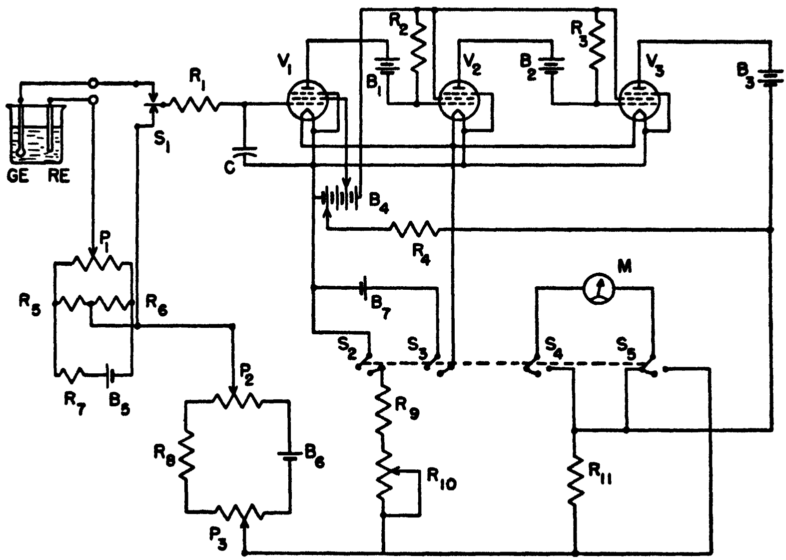


FIG. 8-39. Simplified circuit of the portable glass-electrode pH indicator.

this the instrument is calibrated to give a specific reading by checking a standard buffer solution that has a known pH value. For this adjustment the switch S_1 is thrown to the upper position, resistor R_{10} is set to the proper value for temperature compensation, and the potentiometer P_1 is adjusted so that the meter indicates the pH value specified by the buffer solution. With the dial settings in these positions and the electrodes transferred to a solution of unknown pH, the meter then indicates the pH value directly.

Other electronic methods of obtaining certain chemical titrations and analyses have been developed. One of these methods depends on changes in the dielectric constant as the solution

passes between two plates. In another method, the energy absorption from high-frequency fields forms the basis of conductometric analyses. No electrodes are placed in the solution; however, the inductor in the anode circuit of an oscillator surrounds a glass or plastic tube that contains the solution. Oscillator frequencies in the range of 15 to 20 megacycles per second are commonly used. Current in the anode circuit of the oscillator affords an index of the solution conductivity; titrations are made by noting current changes. In a comparison of known and observed values in titrating numerous solutions, the known and observed end points varied less than 0.1 per cent of the solution volumes.

8-11. The Electrocardiograph

After W. Harvey's discovery in 1616 of the circulation of blood and its dependence on the heart, derangements of circulation gradually came to be associated with possible disease of that organ. Later investigation disclosed that, whenever a part of a muscle contracts, a voltage is generated with the activated portion at a negative polarity with respect to the other portion of the muscle. If the entire strip of muscle is uniformly contracted, both connections are at the same negative potential. Generated voltages have values of the order of a millivolt and a duration as brief as 0.01 second. Since the heart, termed the myocardium, is a muscle that contracts periodically as long as life persists, it, too, develops periodic voltages as it continues to beat.

Anatomically, the heart, which is located in the chest cavity and inclosed in a sac called the pericardium, has two separate receiving and pumping chambers. The ones on the right, termed the right auricle and the right ventricle, constitute the venous unit which receives the blood from the veins and delivers it to the lungs through the pulmonary artery. On its return from the lungs, the blood is received by the left auricle, passes to the left ventricle through valves, and is sent on its way to the arteries. The two auricles, located at the top, contract as a unit, a momentary pause occurs, both ventricles contract, another pause occurs, and the cycle then repeats with an average rhythm of about 70 beats per minute for adults. A normal heart pumps approximately 2650 gallons of blood per day through the blood vessels.

The heart is located in a conducting medium within the body, and the currents that flow are largest in its vicinity and diminish in intensity as the distance increases. Various points on the body, depending on the location and distance from the source, yield different voltage readings. Arms and legs act as linear conductors because the current flow does not extend for any appreciable distance into these extremities. The *electrocardiograph,* first produced by W. Einthoven in 1903, is a very sensitive

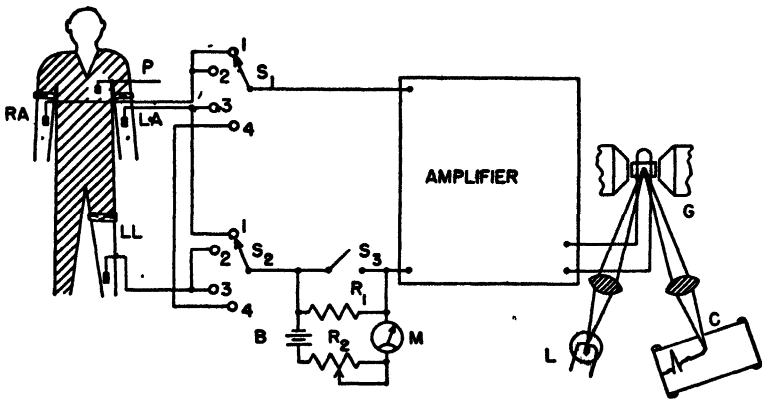


Fig. 8–40. Schematic diagram of an electrocardiograph showing the leads and amplifier-input circuit.

recording galvanometer which records the extremely minute and variable voltages generated by the heart. Instrument leads, which terminate in small nickel-silver electrodes about an inch in diameter, are connected to points on the body where voltage measurements are to be made.

Three standard leads, connected to the two arms and left leg, are normally employed. As shown in Fig. 8–40, the record known as lead I is taken between the left and the right arms; lead II between the right arm and left leg; and lead III between the left arm and left leg. Frequently a record, known as lead IV, is taken between a precordial electrode *P,* placed on the chest, and the left leg. Circuit resistance between any two electrodes is held to 2000 ohms or less by means of a conducting paste between the points of contact and the electrodes.

Aside from the galvanometer-type electrocardiograph, there is another kind that uses an amplifier and an electromagnetic

recorder as shown in the figure. In either type, the instruments are standardized by impressing 1 millivolt on the input circuit and then adjusting the circuit to produce a deflection of 10 millimeters. This abrupt standardizing voltage also checks the

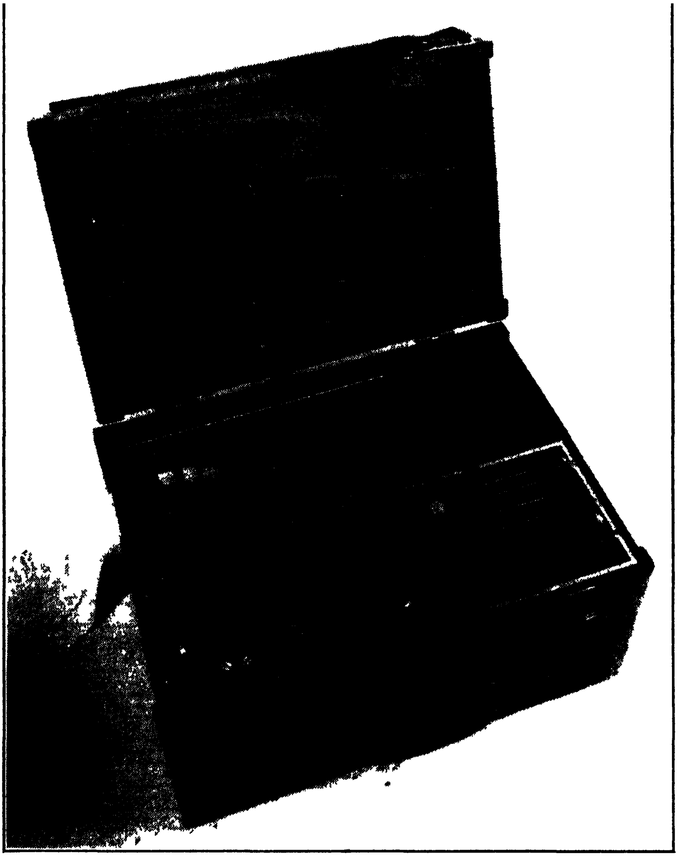


FIG. 8-41. Photograph of the Cardiotron, a portable electronic electrocardiograph *Courtesy Electro-Physical Laboratories.*

instrument for speed of deflection and damping. The amplifier-type instrument operates independently of the electrical resistance of the patient, and, since there are no polarizing effects, it also permits the use of small electrodes, even as fine as points. The amplifier usually consists of a three-stage resistance-capacitance-coupled amplifier with the recording unit connected in the

output circuit of a power stage. Figure 8–41 illustrates a Cardiotron, a portable electronic electrocardiograph.

Electrocardiograms indicate the summation of voltages as they occur between two electrodes and indirectly provide a measure of heart action both in magnitude and time. The three basic waves that occur in most normal records are shown in Fig. 8–42.

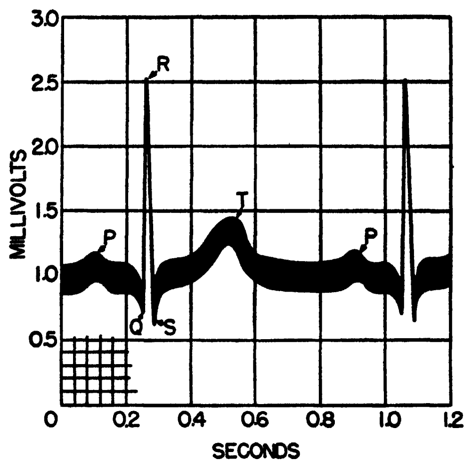


Fig. 8–42. Enlarged trace of a normal cardiogram showing the three predominant waves.

The *P* wave is due to the contraction of the auricles; the *QRS* group is similarly related to ventricular activity; and the *T* wave is caused by the electrical recovery of the ventricular muscle portion of the heart. Each of these waves is separated by a pause or interval.

A defect in the rhythmic time between auricle and ventricle action is indicated by an increase in the *P–R* interval or by dislocation of these two waves. After a heart attack, physical scarring of the heart muscle, known as a myocardial infraction, may occur. This manifests itself in a temporary deviation of the *RS–T* segments and usually shows characteristic changes in the *QRS* groups and *T* waves. Serial electrocardiograms may show progressive changes which allow certain diagnosis of infarction, impossible to obtain from a single tracing. Normal and abnormal electrocardiograms are illustrated in Fig. 8–43. The electrocardiograph is important to the medical profession not

only as an additional diagnostic and treatment aid but also as a research tool in finding a solution for those human ailments that are responsible for approximately one-third of all fatalities.

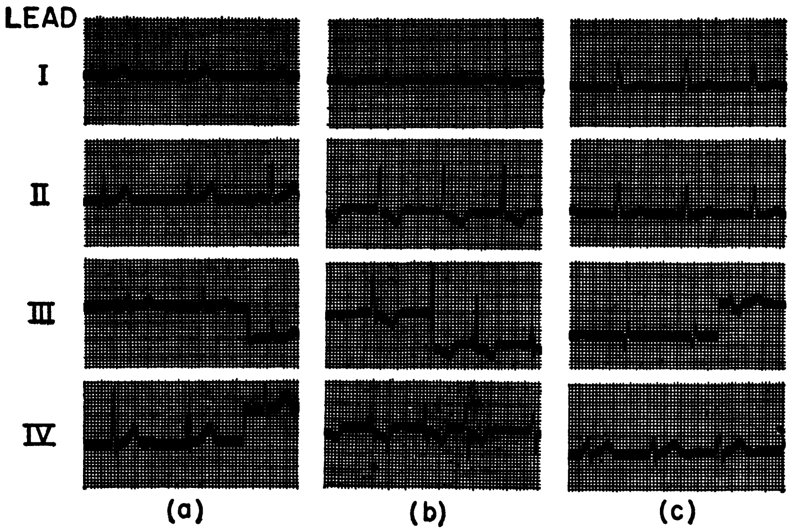


FIG. 8-43. A group of electrocardiograms. (*a*) Normal; (*b*) auricular fibrillation, *T*-wave inversion; (*c*) intraventricular conduction defect. *Courtesy University of Chicago Clinics, Electrocardiographic Laboratory.*

8-12. The Electroencephalograph

Development of extremely sensitive amplifiers and their use in biological measurements in the late 1920's led to the observation that the brain of man produces a fluctuating voltage which varies in frequency between 1 and 60 cycles per second with a dominant frequency of 10 cycles per second. The over-all amplitude of the voltage for normal adults varies between 10 and 50 microvolts and may reach maximum amplitudes of about 100 microvolts. It varies with age, disease, and sensory stimulation, among other factors.

A diagnostic instrument known as the *electroencephalograph* is used to record the voltages generated within the brain by applying electrodes at specific locations on the head. Diagnosis is based primarily on the frequencies and secondarily on the amplitude of the recorded signals. Frequencies of approximately 10 cycles per second are termed alpha waves; those from 15 to

60 cycles per second, beta waves; and those slower than 8 cycles per second are designated as delta waves.

Electron tube amplifiers of the resistance-capacitance-coupled type, connected in push-pull, as shown in Fig. 8–44, are commonly employed. Properly designed push-pull circuits are capable of amplifying large amplitude signals with little distortion and are relatively free from power-line and radio interference. Input leads are connected to terminals 1 and 2. A number of stages of the type shown in the figure are required in order to obtain the requisite voltage amplification of 10,000,000 or more.

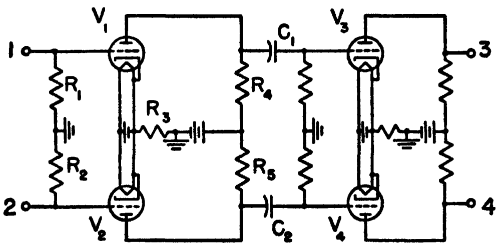
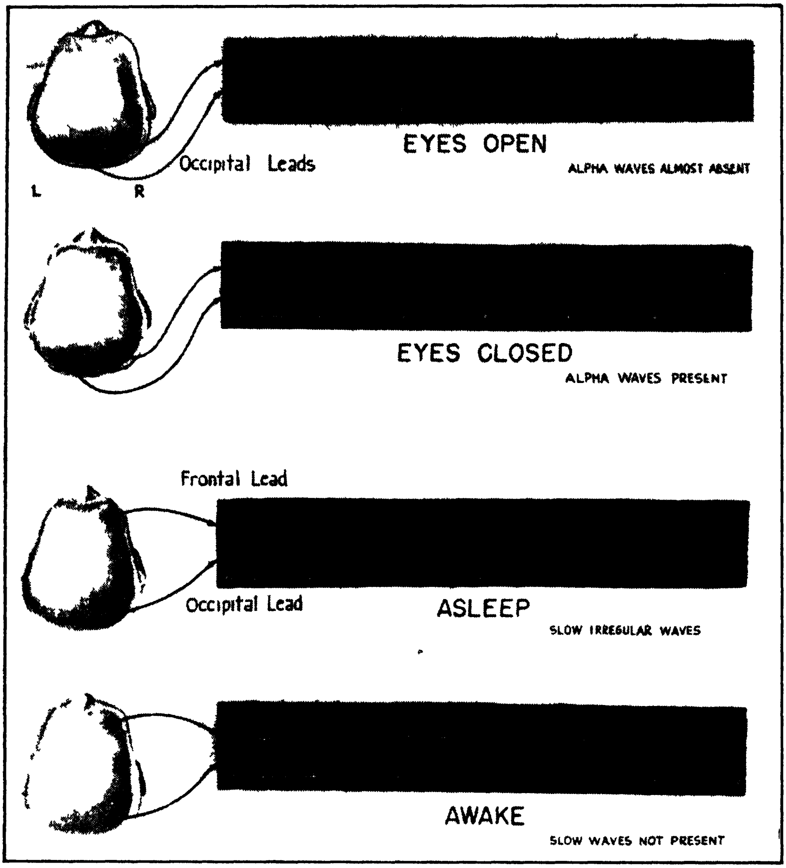


Fig. 8–44. Circuit of a resistance-capacitance-coupled push-pull amplifier.

The recorder is connected to output terminals 3 and 4. Einthoven string galvanometers were used in the first instruments for making recordings, but more recently crystal and electromagnetic recorders have come into extensive use. Representative recordings require from 5 to 20 minutes, and, consequently, an inkwriting recorder that makes the record available immediately has definite advantages. The recorder and the amplifier must, of course, respond uniformly to all voltages with frequencies to about 100 cycles per second.

Any one exploring circuit commonly consists of two small metal-plate electrodes, which are coated with a conducting paste and attached to the cortex with a small quantity of cellulose acetate. Electrodes are located at specified positions, Fig. 8–45, although one of the electrodes is sometimes attached to the ear lobe for use as a common or indifferent electrode. The voltage generated under each electrode is predominantly recorded, and, when one electrode is used as an indifferent one, explorations for maximum deviations from the normal pattern may be made by taking readings with the other electrode placed at varying positions on the cortex. A major cortical lesion is localized



(*a*)

Fig. 8-45. Diagram showing location of electrodes and representative recordings of (*a*) normal and (*b*) abnormal brain conditions *Courtesy University of Chicago Department of Electroencephalography.*

quite easily by determining the electrode position where a maximum abnormal voltage occurs.

Some clinical results obtained from this electronic instrument may be of interest. The predominant frequency gradually changes from 1 to 3 cycles per second in infancy to 10 cycles per second for a normal adult, reached between the ages of 14 to 20 years. Any sensory stimulation that attracts the subject's attention or interest decreases the normal waves and causes them

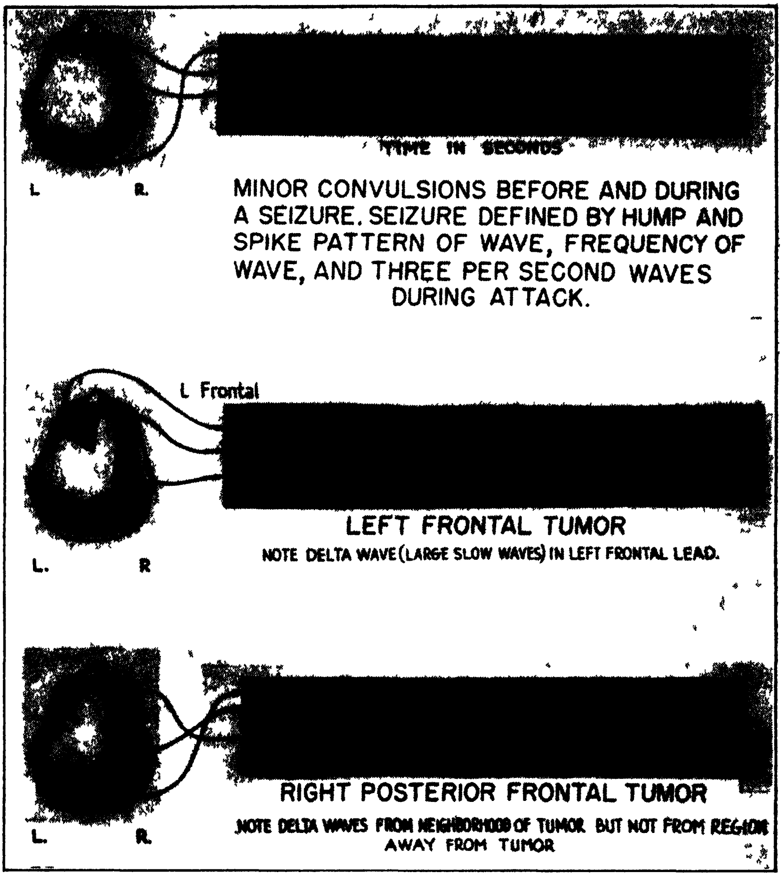


FIG. 8–45 (*b*).

to be less regular. Clinical value of the instrument lies in the diagnosis and localization of epilepsy, brain tumors, brain hemorrhage, and certain other cortical lesions, by analyzing the electroencephalogram. Typical recordings, representative of normal and abnormal brain conditions, are illustrated in Fig. 8–45.

Problems

1. What is the effect in the operation of the thermocouple and ionization gauge, Fig. 8–2, if (*a*) the resistor R_{12} open-circuits, and (*b*) one of the terminals of the tube V_2 fails to make contact?

2. In the electronic counter, Fig. 8–3, explain (*a*) why a positive pulse

impressed on the input circuit has no effect, and (*b*) why opening the cathode circuit of all the left-hand triode sections resets the circuit with all lamps extinguished.

3. Explain in detail why any residual reading of the meter of the tire inspector, shown in Fig. 8–7, is reduced to zero by suitable adjustment of the coupling between the primary and secondary windings of the balance coil.

4. What in your opinion are the factors that limit the sensitivity that may be built into a vacuum-tube voltmeter for measuring (*a*) direct voltages, (*b*) alternating voltages at audio frequencies, and (*c*) alternating voltages at very high radio frequencies?

5. Analyze in detail the action of the phase-selective demodulator in the measurement of oversize and undersize parts in the comparator gauge shown in Fig. 8–13.

6. Tabulate a list of transducers or pickups suitable for vibration analysis. Outline their basis of operation, and indicate if they are responsive to measurement of displacement, velocity, or acceleration.

7. Familiarize yourself with the method of transmitting time signals from radio station WWV by listening on a short-wave radio receiver tuned to one of the frequencies listed in Sec. 8–8. Plot the daily time deviation of your watch by making observations 24 hours apart over a period of 6 days.

8. Calculate the voltages and plot the voltage versus *p*H curves for a calomel reference electrode and a glass electrode according to Eq. 8–18 for *p*H values ranging between 4 and 10 in steps of 0.5 *p*H. How many millivolts change occurs for a change of (*a*) 0.01 *p*H, (*b*) 0.10 *p*H?

9. The battery B_4 in the *p*H indicator, Fig. 8–39, has two taps in addition to its end connections. Trace both of these circuits and also the one connected to the most positive terminal of the battery, and justify their existence.

10. Explain in detail why the amplifier, shown in Fig. 8–44, is not suitable for insertion in the amplifier block of the electrocardiograph, Fig. 8–40.

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9·

Electronics in Communication

Early efforts in electronics were directed to its application in the field of communication. Radiotelegraphy, long-distance telephone communication, radiobroadcasting and reception, radiotelephony, navigational aids for airplanes and ships, and finally television were developed in sequence. Each of these has taken its place as an indispensable part of our modern life. Space does not permit more than a casual survey of these systems; they are reviewed to show the broad scope of electron-tube applications to new public services within recent years.

9-1. Wire Communication

In the telephone, a transmitter modulates the amplitude of an electric current in conformity with sound-pressure variations of the air; the current variations are transmitted over an open-wire line or a cable and actuate a receiver at the other subscriber's station. Signal attenuation was a serious factor in early long-distance communication, and every possible care was taken to conserve signal strength. Nevertheless, during 1911 telephone service was opened between New York and Denver, a distance of 2000 miles, and in 1913 an underground inductively-loaded cable was placed in operation between Boston, New York, and Washington, a distance of over 420 miles. But with the development of vacuum tubes and special amplifiers, termed *repeaters,* the signal strength was increased at each of the uniformly spaced repeater stations along the line, and transcontinental telephone service between New York and San Francisco was established in 1915. Technical problems of long-distance telephony were grad-

ually solved, and today a subscriber can speak to any one of the thirty-odd million interconnected subscribers in the United States. Popularity of this service is attested to by the fact that over 200,000,000 long-distance telephone conversations were conducted in 1946.

Telephone repeaters for two-way communication need to amplify equally well in both directions. A simplified circuit of a bidirectional amplifier is given in Fig. 9–1, in which the terminating lines are designated as East and West circuits. Each

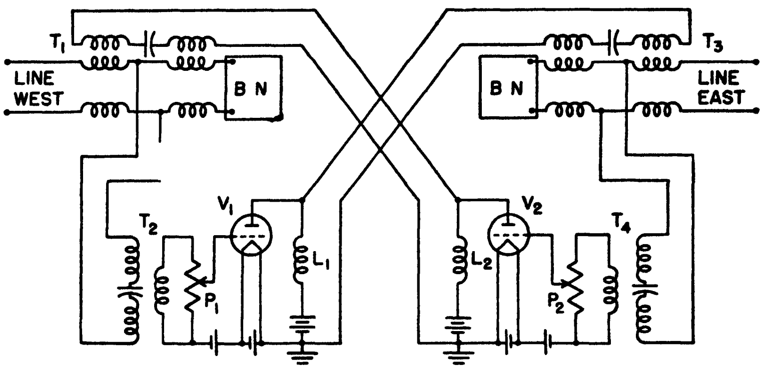


FIG. 9–1. Simplified circuit of a bidirectional amplifier.

line is connected to a special three-winding transformer, termed a hybrid coil, and to a balancing network composed of resistors, inductors, and capacitors. The hybrid coil separates the output circuit of one tube from the input circuit of the other, and the balancing network simulates the impedance of the line connected to the repeater. Let us assume that signals are arriving on line West. With a balanced network, one-half of the incoming energy is dissipated in network *BN* in the form of heat, while the other half is impressed through transformer T_2 on the input circuit of tube V_1. Amplified signals are impressed on hybrid coil T_3, where the energy again divides between line East and the associated balancing network. Either hybrid coil feeds some of the energy in its output circuit back into the input circuit if its line is imperfectly balanced; if both are poorly matched, there may be sufficient feedback to cause the circuit to oscillate. Automatic compensating devices have been developed which keep balancing networks in constant adjustment even though the line

resistances of long circuits change with temperature variations along the line. This standard repeater is designed to have a maximum gain of 19.5 decibels. Repeater stations for open-wire lines are located approximately 100 miles apart.

Telegraph and high-frequency carrier-current circuits also utilize the same pair of wires to provide additional communication channels. Electrical filters separate the carrier currents, and rectifiers demodulate the signals, which are then transmitted

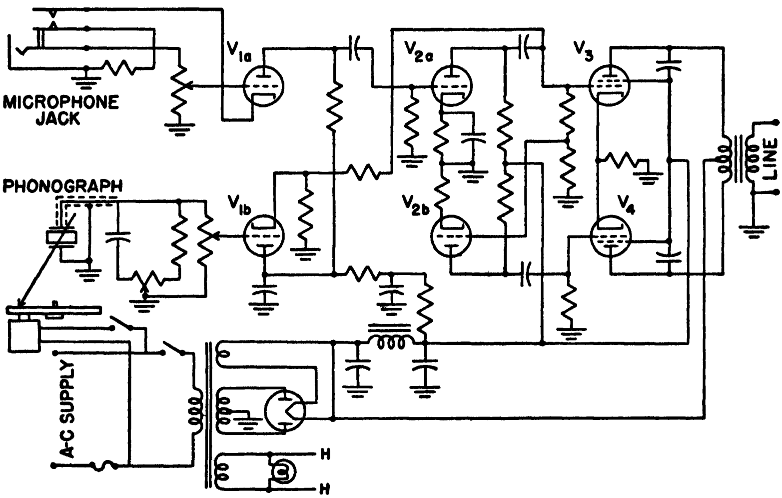


FIG. 9–2. Circuit of a public-address system arranged for either speech or phonograph input. *Courtesy Pacific Sound Corporation.*

over local lines. As many as sixteen simultaneous conversations can be transmitted over a circuit consisting of a single open-wire pair. In the recently developed coaxial cable system, 480 telephone circuits can operate simultaneously over two coaxial conductors.

By comparison with the highly complex adaptations of electron tubes in the vast telephone network, a two-station interoffice calling or communicating system represents one of the simplest of tube applications to a wire circuit. The system consists of a microphone, amplifier, rectifier, and loud-speaker built in a small cabinet and connected to a similar unit in the same building. A number of these units may be interconnected, and one or more desired stations are selected by throwing appro-

priate key switches. Two-way communication is obtained by switching from a talking to a listening position. A modification of a single unit is useful as a public-address system, an amplifying device that extends speech and music in auditoriums, for civic concerts, and the like; it also serves for paging, announcements, and entertainment in large stores and industrial plants. The



FIG. 9–3. Control room of a public-address system. *Courtesy Woodward Governor Company.*

circuit of a simple public-address system, arranged for either speech or phonograph input, is shown in Fig. 9–2. A preamplifier tube V_{1a} is used in conjunction with the microphone, and a *phase inverter tube* supplies the input to one side of the push-pull stage, composed of tubes V_3 and V_4. Aside from these special features, the amplifier is similar to those previously described.

Large public-address installations are much more complex. The system illustrated in Fig. 9–3 is installed in a plant and is used for general announcements and paging. Since monotony and operator fatigue are relieved by music played at intervals, phonograph records and radiobroadcast programs of general

interest or importance may be reproduced or they may be recorded and reproduced later. This public-address system has a total output of 500 watts, obtained from ten 50-watt amplifiers. There are twelve preamplifiers for twelve microphone input circuits and four driver amplifiers so that four different programs can be transmitted simultaneously to various parts of the plant. One or more of the ten amplifiers can be switched to any one of the four programs. Of the total of 165 speakers installed in the plant, there are 64 recessed ceiling speakers in the machine shop, mounted on 20-foot centers. (See Fig. 1–1.) Dual recording turntables may be used to record continuous programs from the plant auditorium, which seats over 500 people. Emergency paging is possible from any telephone in the private automatic exchange system, and automatic limiters on all the paging circuits maintain a constant paging volume.

9–2. Radio Communication

The famous experiments of Guglielmo Marconi at the turn of the century and his first transatlantic messages in 1903 were followed by intensive development and application work. Shore stations were built and ships were equipped with spark and high-frequency generator-type radiotelegraph transmitters and crystal-type receivers. However, radio's great value was only fully appreciated several years later when dramatic rescues were made at sea and continuous contact between ships and shore was established. In 1915 the human voice was transmitted successfully from Washington to Paris and from Washington to the Hawaiian Islands; these experiments directed attention to the vacuum tube as the key to reliable radiotelephone transmission and reception. A few years later, in 1921, F. Conrad founded the first radiobroadcast station operating on regular schedule. In the meantime, national and international regulations were established and definite frequency bands were assigned for radiobroadcast, for radiotelegraph point-to-point service, for marine service, for experimental and amateur use, for distress signals, and later for facsimile, television, radar, aircraft navigational aids, and other services.

The frequency band set aside for amplitude-modulated broadcast service covers the frequencies from 550 to 1600 kilocycles per second, and in the United States there are approximately

1100 broadcast stations with powers ranging from 250 watts to 50 kilowatts. Since the transmission of audio frequencies from about 20 to 5000 cycles per second is required for acceptable reproduction at the receiver, amplitude-modulated carriers can be placed only as close as 10 kilocycles apart in the electromagnetic spectrum. Consequently, a number of stations, particularly those serving local areas, are assigned identical frequencies;

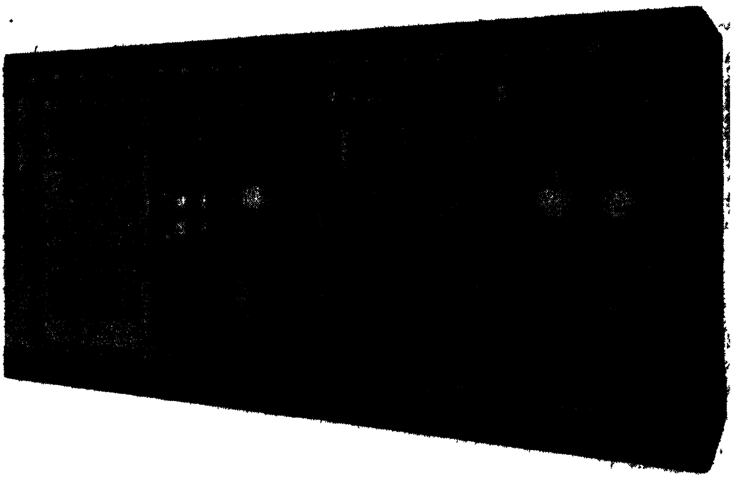


FIG. 9–4. View of a 5-kilowatt radiobroadcast transmitter with the front panels removed. *Courtesy Raytheon Manufacturing Company.*

there are only 106 channels in that portion of the spectrum. Basically a radiobroadcast transmitter consists of a rectifier to supply the required d-c power, a crystal-controlled oscillator, a number of radio-frequency amplifier stages, speech and music input equipment with an audio-frequency amplifier, an output circuit where the carrier is modulated, and a suitable antenna and ground system. Figure 9–4 shows the interior of a typical 5-kilowatt radiobroadcast transmitter, and Fig. 9–5 illustrates the control room of a broadcast station.

A vertical radiator is used as an antenna to obtain the maximum transmission of the signal that travels along the surface of the earth. With uniform soil conditions and no reflecting surfaces the radiated pattern of a single vertical radiator is

circular, but by suitably locating additional radiators and connecting them to the transmitter so that the current in them is phase-displaced from that in the main radiator, a field pattern resembling a cloverleaf, a cardioid, or any one of a large number of directive patterns may be obtained. A radiating system of this type directs the energy to the service area to be covered and also greatly attenuates the signal in other directions. This

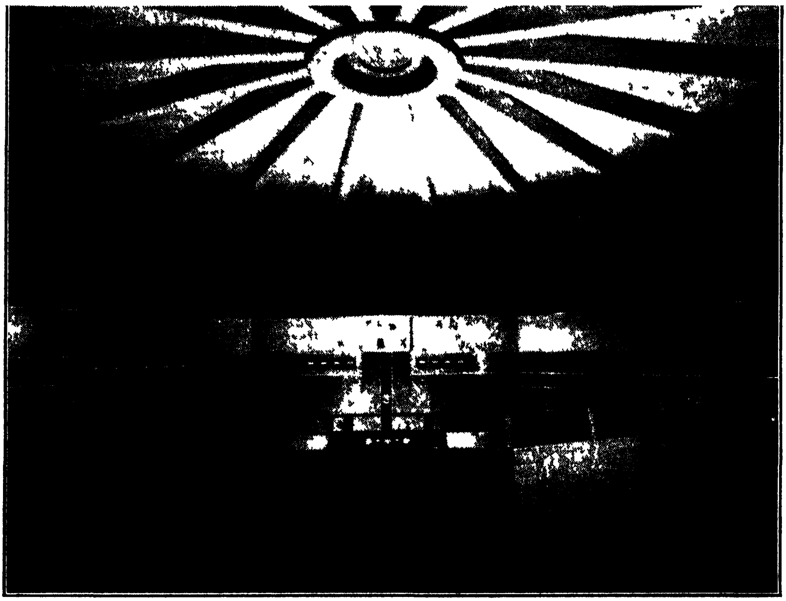


FIG. 9–5. Main operating room of the KNX 50-kilowatt radiobroadcast transmitter at Torrance, California *Courtesy Columbia Broadcasting System.*

arrangement permits another transmitter, equipped with a similar antenna array and located some distance away, to operate on the same frequency and prevents mutual interference. A modern station, provided with an array of three vertical radiators for directional broadcasting, is illustrated in Fig. 9–6.

Over 70,000,000 radiobroadcast receivers are in use in the United States; they range in size from small portable, self-contained units to those of large console type that incorporate automatic tuning, magnetic wire or tape recording, phonograph reproduction, and the like. The circuit of a typical 5-tube radio

receiver is given in Fig. 9–7. Tube V_1 combines the functions of oscillator, amplifier, and mixer; tube V_3 performs as a demodulator and audio-frequency amplifier. Automatic volume control is achieved by regulating the grid-bias voltage on tubes V_1 and V_2 in proportion to the strength of the carrier impressed on the rectifier portion of tube V_3.



FIG. 9–6 Transmitter building and the directional antenna array of radiobroadcasting station WTOP, formerly WJSV, at Washington, D. C. *Courtesy Columbia Broadcasting System.*

Several short-wave, that is, high-frequency, bands are also set aside for radiobroadcast transmissions; they serve overseas territories and provide home contacts for passengers and crews on transoceanic steamers and airplanes. Other frequencies are reserved for the transmission of municipal and state police broadcasts to officers on motorcycles and in squad cars, to sheriff's offices, and to the control rooms of similar radio stations in adjacent states. Definite frequency bands are also set apart for the use of the thousands of radio amateurs.

Much of the message traffic and press transmissions between countries of the world, as well as between ships and shore, is carried on by means of radiotelegraph service. Radiomarine service offers the general public an efficient long-range radiotelegraph communication system which maintains contact with vessels in all parts of the world. Shore stations are constantly

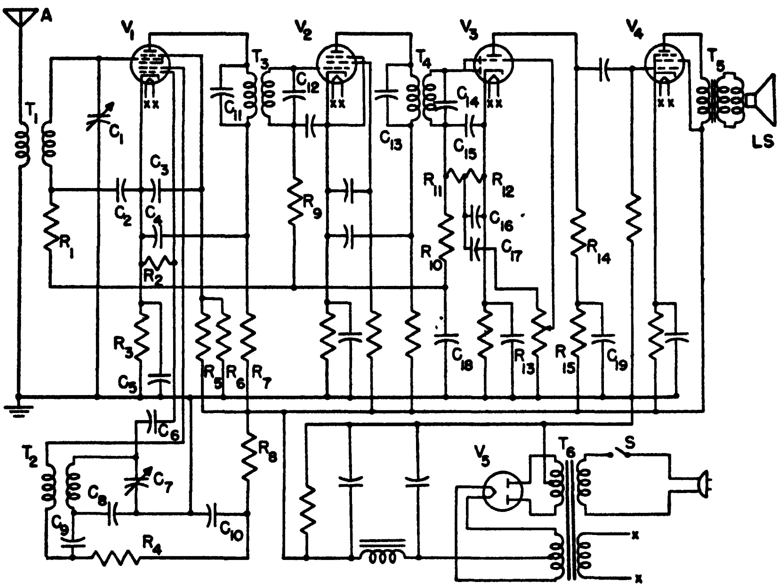


Fig. 9–7. Circuit of a 5-tube superheterodyne radio receiver.

on the alert to render aid to vessels in distress; they provide free medical diagnosis and prescription for sick and injured personnel on ships beyond reach of a doctor, and broadcast weather reports and news bulletins.

In its simplest form a radiotelegraph transmitter comprises a crystal-controlled radio-frequency oscillator followed by an amplifier and connected to a suitable antenna and ground. The high-frequency oscillations may be modulated with an audio frequency and then transmitted in the form of the dots and dashes of the telegraph code, or the interrupted carrier may be transmitted unmodulated, in which event the receiving station must supply a high-frequency carrier that heterodynes with the incoming signal and makes the transmitted signal audible as a

beat frequency. The load varies between zero and full load with every dot and dash, and various methods of loading have been developed to avoid the severe burden on the power supply.

The basic principle of frequency modulation has been applied to code transmission in the development of a frequency-shift radiotelegraph system where the transmitter radiates full power at one frequency for the signal, comprising the dot or the dash and often termed a mark, and another frequency for the space. Comparable with frequency modulation in radiobroadcasting, a considerable improvement in signal-to-noise level is obtained; a 20-decibel increase in signal-to-noise ratio is not unusual. Transmitting equipment is arranged so that the frequency for a mark is increased while that for a space is decreased, total frequency shift being standardized at 850 cycles, although the shift may be varied from 400 to 1200 cycles for special services. This method is also applied to the transmission of teletype mark and space signals; to facsimile transmission, where one frequency corresponds to black and the other to white; and to picture transmission where gradations between black and white are represented by frequencies lying between the two extremes.

Transmission and reception of code require highly trained personnel, but with a strong signal and an absence of noise tremendously high speeds may be attained by using automatic equipment. For example, a small mobile 400-watt frequency-shift transmitter in France in 1946 regularly transmitted over a million words a month of press traffic to this country at a rate of 500 words a minute, where in former days a 50-kilowatt transmitter had trouble in maintaining the circuit. Transmission of this type was used by Admiral Byrd in his South Pole expedition of 1939–1940, and pictures coming over 8000 miles from a small 500-watt transmitter were received with the clarity of standard wirephoto pictures. Regular transmissions from London, Buenos Aires, Tokyo, and other locations are now commonplace. Figure 9–8 illustrates a photo-optical unit, termed a Photo Transceiver, which scans and records photographs, blueprints, maps, newsprint, typewritten copy, or similar material that has gradations between black and white.

The problem of long-distance overwater telephony was met in 1927 by the establishment of a transoceanic radio extension link between London and New York to furnish telephone service

between the two cities and to permit telephone conversations between the United States and Europe through the auxiliary use of toll wire extensions. Both long- and short-wave radio bands, covering frequencies from less than 50 to 100 kilocycles per second and from 6 to 23 megacycles per second respectively, have been found to be well suited for these transmissions. Suc-

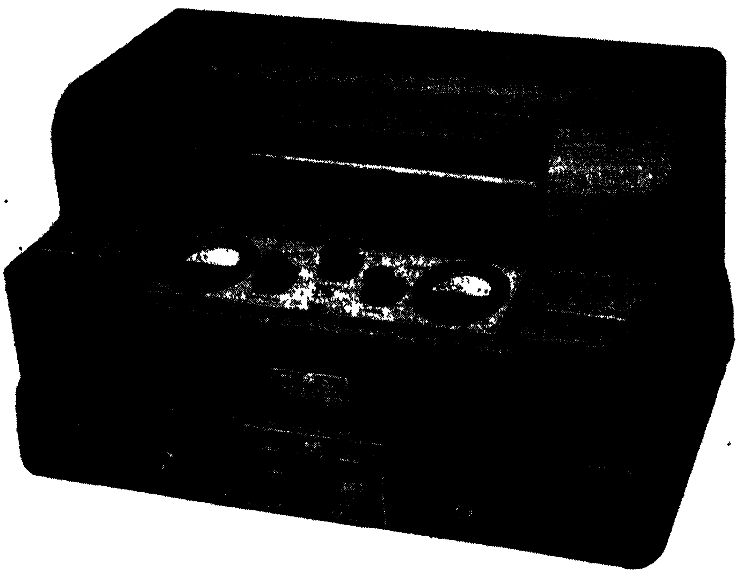


Fig. 9–8. Photo Transceiver, a terminal instrument that transmits and receives photographs, newsprint, and the like by means of frequency-shift radiotelegraph signals. *Courtesy Press Wireless, Inc.*

cess of the service resulted in its expansion, and now there are several radiotelephone channels to London and others to the West Indies, Australia, China, South America, and other parts of the globe. This service provides interconnection with nearly all telephones throughout the world. Usually any one radio circuit consists of a transmitter which beams its energy to a receiving station located in a disturbance-free area, where the signal is suitably amplified and transmitted over land lines to the main office. The return signal is delivered to a transmitter operating at a different frequency and geographically removed from the

receiving station. Wire circuits between each transmitter and receiver terminate in a central office where connections are made to standard subscriber equipment.

One of the most modern of communication installations on a passenger liner is that on the *S.S. Queen Elizabeth,* the largest passenger ship afloat. Four high-power transmitters, operating on short-, medium-, and long-wave radio bands, are housed in a special room and remotely controlled from the main control room which is illustrated in Fig. 9–9. Separate antennas permit



FIG. 9–9. Main radio control room of the *S.S. Queen Elizabeth. Courtesy International Telephone and Telegraph Corporation.*

simultaneous transmission and reception of radiotelegraph signals, automatic high-speed recordings, teletype, and radiotelephone calls. The radiotelephone service permits a passenger to place a call to a subscriber in any country whose telephone service is connected to an international exchange or to passengers on other radiotelephone-equipped ships as easily and quickly as an ordinary telephone call. Special receivers in the main control room are tuned to receive broadcast programs, and these are redistributed to various parts of the ship.

Ultrahigh-frequency radiotelephone communication has been developed for point-to-point service within line of sight and comprises such installations as the eight-channel microwave radio-

telephone systems, placed in service in 1946, between Los Angeles, California, and Catalina Island, and between Barnstable, Massachusetts, and Nantucket Island. In the same year the first urban mobile system went into operation, and at the end of the year regular telephone service was being given to more than 600 motor vehicles in 25 cities.

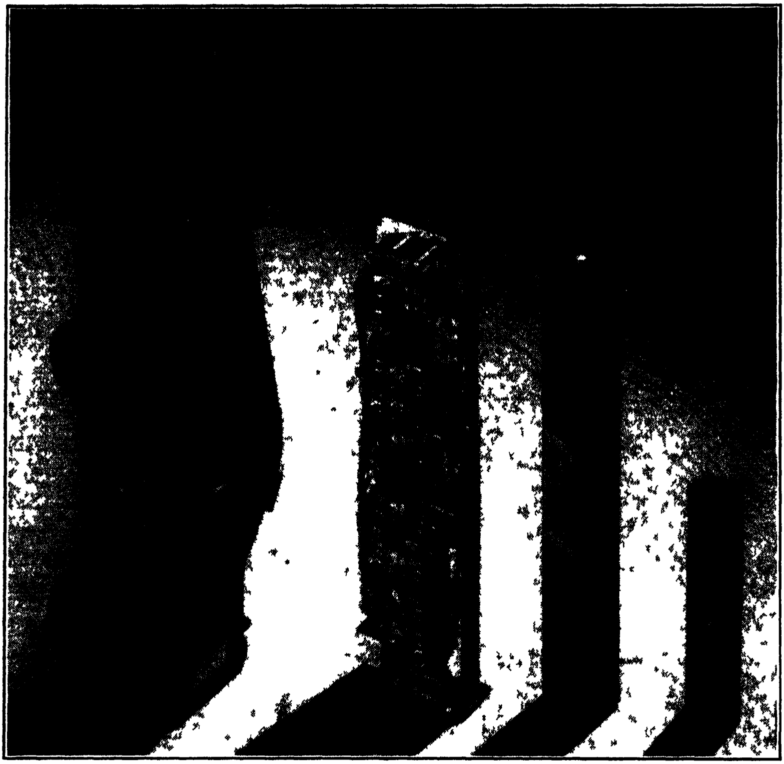


FIG 9–10 The handie-talkie, a radio transmitter and receiver of the portable type used by the Signal Corps, United States Army *Courtesy Galvin Manufacturing Corporation*

During the last decade, two-way radio communication in the short-wave bands, such as the one in the 152- to 162-megacycle-per-second region, has been perfected for use by police, public-service conveyances, railroad yards and freight trains, and harbor service. In a typical squad-car installation, the transmitter and receiver are mounted in the luggage compartment; the con-

trol panel, microphone, and loud-speaker are located on or beneath the automobile instrument panel; and the rodlike antenna, used for transmission and reception, is mounted through the roof or to one side of the luggage compartment. The automobile battery supplies the necessary power, and a special generator keeps it charged. Two-way communication received a tremendous impetus during World War II, and portable units were developed, of which the walkie-talkie and the handie-talkie are notable examples. The handie-talkie is illustrated in Fig. 9–10,

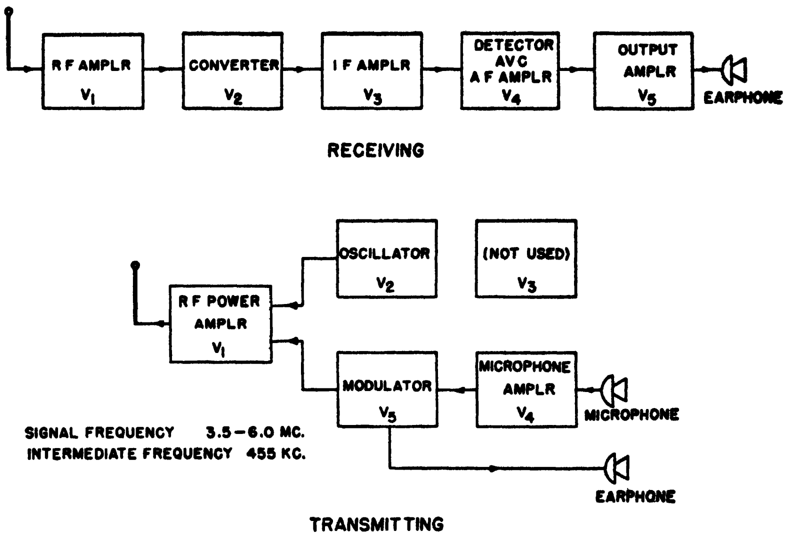


FIG. 9–11. Block-type diagram of the handie-talkie, showing tubes used while receiving and transmitting.

and a block diagram, indicating the functional use of the tubes during transmitting and receiving, is given in Fig. 9–11.

Early television was confronted with a number of technical difficulties and harassed by many problems. But with the development of modern camera tubes one of the most serious obstacles, which is the translating or dissecting of a moving scene, sometimes not too well illuminated, into corresponding current impulses that could be transmitted after amplification, has been overcome. Technical progress has also been made on the cathode-ray tube which reconstructs the picture image and makes it visible at the receiver. A simple television receiver consists of

a combination of two receivers; one is arranged to reconstruct the televised scene, while the other reproduces the associated speech and music. The major components that comprise a conventional television receiver are given in the block-type diagram, Fig. 9-12. Television requires the transmission of a large number of individual picture elements per second, and this, in turn, prescribes the need for a very high broadcast frequency. This

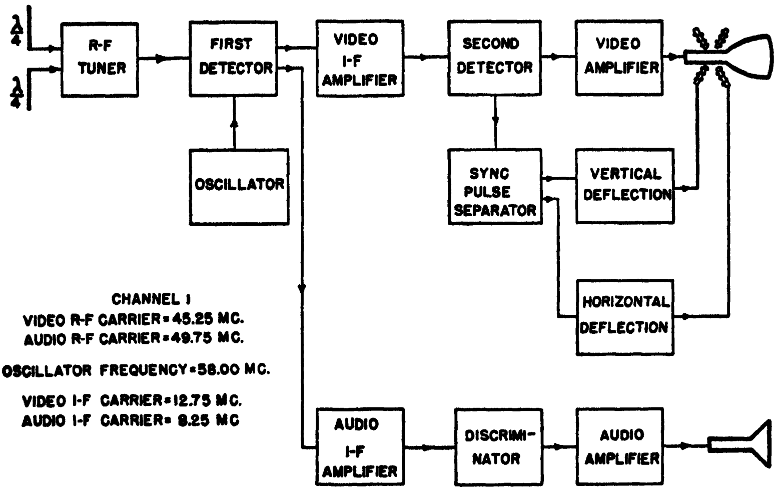


Fig. 9–12. Block-type diagram of the major components of a television receiver.

service is met at present by the use of six channels in the range between 44 to 88 megacycles per second, and seven other channels with frequencies between 174 and 216 megacycles per second. Each channel is 6 megacycles wide and provides for a video signal carrier with a spread of 4 megacycles and also for the F-M sound signal carrier with a spread of 50 kilocycles. Because of the transmission characteristics of ultrahigh frequencies, television transmission and reception is limited to line-of-sight. The same limitation is encountered in the transmission and reception of frequency-modulated broadcasts, where the present assigned frequencies range between 88 and 108 megacycles per second.

Unlike wire transmission of studio programs for radiobroadcasting, relaying of high-frequency television signals between transmitters requires special coaxial cable with frequent re-

peaters. Considerable experimentation is in progress, and relay links are being established to direct the high-frequency signals from one metropolitan area to another by means of radio. During World War II high-frequency relay stations, one of which is shown in Fig. 9–13, were installed to beam radio communications from one fixed position to another. Currently a radio relay system is under construction to connect New York and Boston. The purpose of this system, which will embrace seven stations in addition to the terminals, is broadband transmission of microwave energy for television, radio, and long-distance telephone signals. Power and relay equipment will be housed within each tower building, and an array, consisting of four metal antennas covered with a translucent plastic sheath for protection from the weather, is to receive the signals from one station and relay them to the next.



FIG. 9–13. United States military radio relay station on a tower at Heidelberg, part of the Weisbaden-Augsburg circuit in Germany. *Courtesy Bell Telephone Laboratories.*

Ordinary television reproduces an image in black and white; however, color television is being developed; it was broadcast for the first time in 1940 in New York. The system is fundamentally similar to ordinary black-and-white television except that a rotating color drum allows the camera tube to receive red, blue, and green light in sequence. At the receiver an analogous, rotating, tricolor disc, synchronized with the color drum

at the transmitter, reconstructs the image in color through the aid of a cathode-ray tube developed especially for color pictures. Figure 9–14 shows a black-and-white reproduction of a color television receiver operating on this principle. It is equipped with an optical system that projects a 17 × 22 inch image on the screen. In 1947 an all-electronic method for obtaining color



Fig. 9–14. Black and white reproduction of a color sequence television projection receiver *Courtesy Columbia Broadcasting System.*

television was announced in which the televised scene is directed through three color-selective optical systems to three camera tubes where the red, green, and blue images are formed. An electron switch permits the images to be scanned in rotation, and the signals are broadcast. At the receiver a similar electron switch, which operates in synchronism with the one at the transmitter, directs the received signals in sequence to three separate Kinescopes, where the red, green, and blue images are reproduced. These separate images are reflected on a screen to produce the composite color picture. As with ordinary television, both color

television methods use an additional radio-frequency channel for the accompanying speech and music.

9–3. Echo Systems

Determination of a radio echo and the observation of the elapsed time between the transmitted pulse and its echo gives

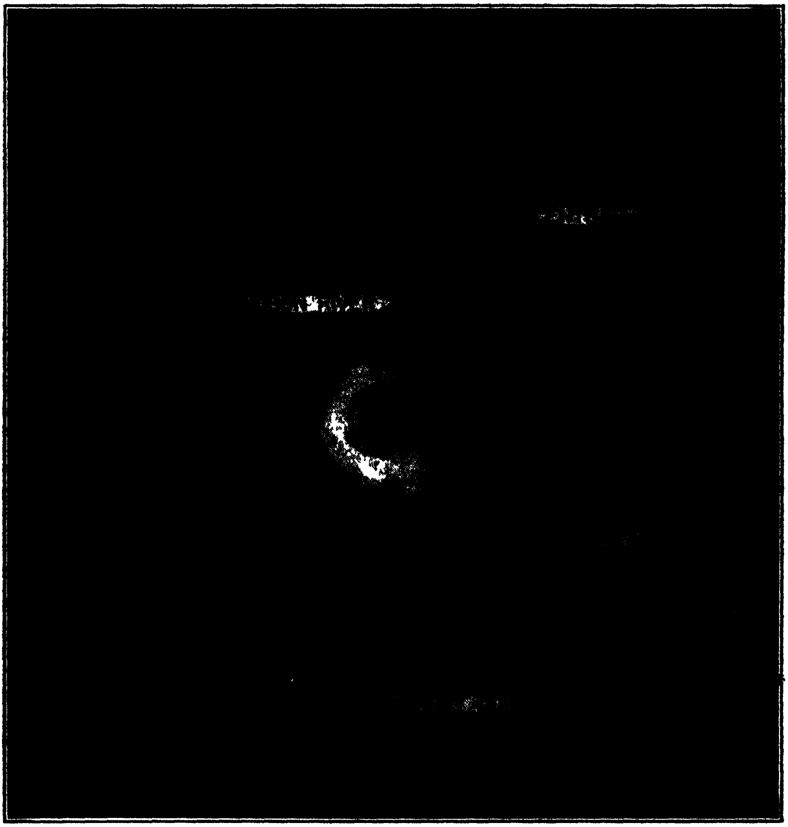


FIG. 9–15. Plan-position indicator trace on a radar oscilloscope showing image of New York City. *Courtesy United States Army Air Forces.*

important but only partial information. The basic system was soon modified to disclose a number of consecutive echoes from various parts of an area in the form of a polar plot on the screen of a cathode-ray tube. In this system, known as a plan-position indicator, the electron beam in the cathode-ray tube

starts periodically at the center and moves toward the edge of the screen at a constant velocity, its position corresponding to the position of the radiated pulse in space. Depending on the nature of the reflecting surface, any echo causes intensity modulation of the cathode-ray beam with a resulting change in brilliancy of the fluorescent spot on the screen. In airborne radar equipment, where observations are made directly beneath the airplane, the antenna array, mounted either in the nose or in the lower portion of the ship, also tilts radially outward periodically, and the position of the spot on the screen provides a measure of the distance and direction of the reflecting surface. The antenna array also rotates and advances a fixed angular amount after each radial excursion. Coils carrying a constant current are suitably displaced about the stem of the cathode-ray tube and are made to revolve in synchronism with the antenna. Their magnetic field causes the beam to rotate, producing a map-like image of the reflected radio energy. A photograph of a plan-position indicator trace, taken by means of airborne radar and showing the image of New York City, is shown in Fig. 9–15. In effect, the pilot in an airplane has a view of the earth similar to what he might see at night if the airplane illuminated the ground with a giant rotating searchlight. Buildings and bridges reflect radio energy, but a body of water appears dark. The pattern also discloses slightly brighter range circles that indicate

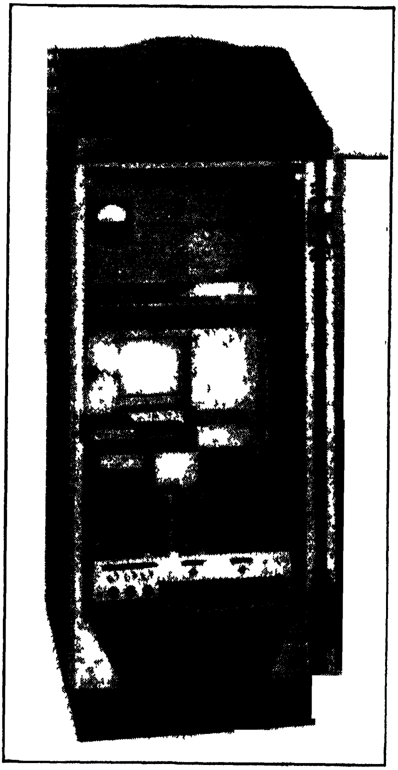


FIG. 9–16. Marine-type radar receiver showing internal construction *Courtesy Westinghouse Electric Corporation.*

distances from the point of observation. Radar-equipped merchant marine ships can proceed at full speed at night without risk of collision with other vessels or icebergs, and fogs no

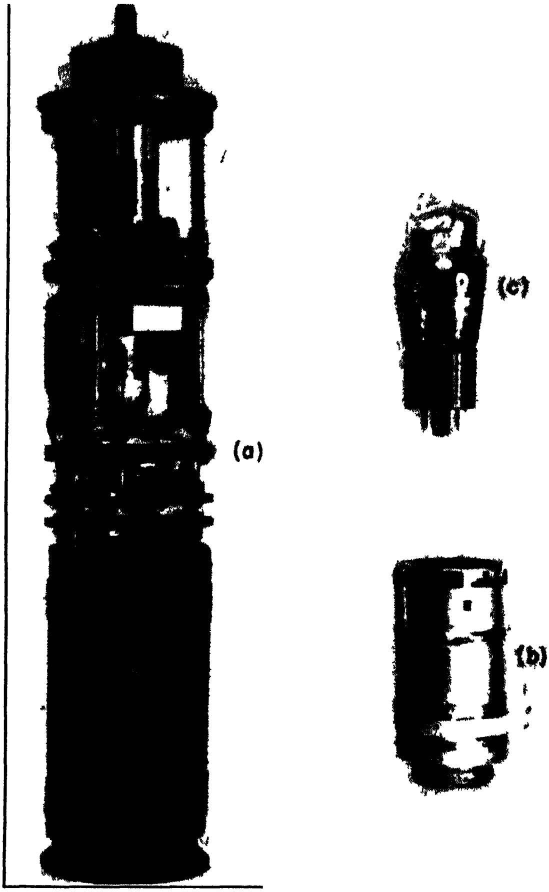
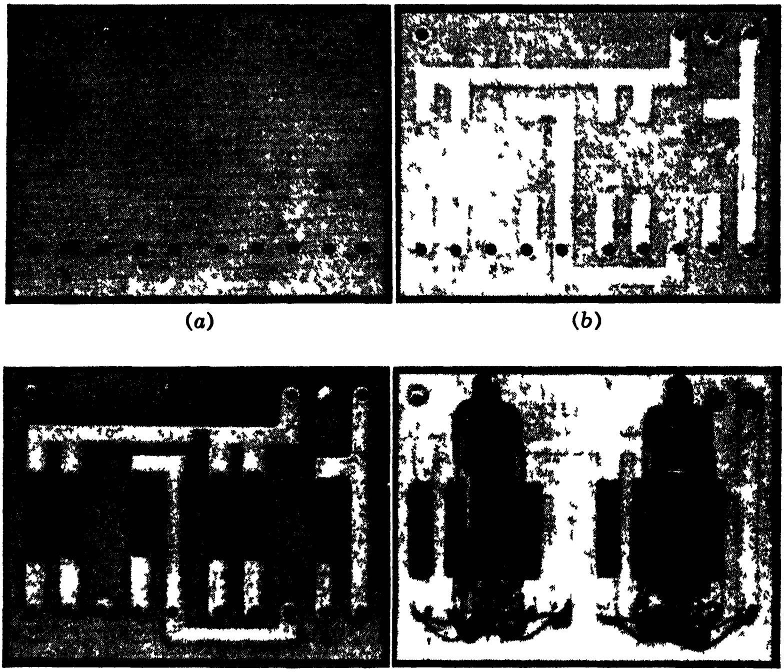


FIG 9–17 (*a*) Early radio proximity fuze. (*b*) Miniature mortar fuze. (*c*) Conventional radio rectifier tube shown for size comparison. *Courtesy National Bureau of Standards.*

longer reduce their speed or delay their entry into harbors. A typical radar receiving instrument suitable for mounting on the bridge of a ship is illustrated in Fig. 9–16.

Radar principles have also been applied to the fields of control and measurements. One of the most spectacular adaptations is

that of the radio proximity fuze which automatically explodes a projectile at the proper distance from the target, the detonation being governed by the received echo from radio-frequency signals. The fuze consists of a self-contained power supply, transmitter, receiver, antenna, and detonator. A shell equipped with



(a) (b) (c) (d)

FIG 9–18 Four successive steps in making a printed electronic circuit (a) Steatite plate after firing and shrinkage, (b) plate with circuit wiring, (c) same with the addition of resistors, (d) assembled unit with miniature tubes *Courtesy National Bureau of Standards*

a proximity fuze begins to transmit a steady signal, radiated by a small antenna, shortly after it leaves the bore of the gun The detonating signal is obtained by the combination of the signal transmitted by the local oscillator and that received by reflection from the target, that is, it depends on the difference beat frequency brought about by the Doppler effect Figure 9–17 illustrates the first successful radio proximity fuze, made in 1941; it was attached to the tail of a bomb and trailed a

whiplike antenna. Beside it is shown one of the later miniature mortar fuzes and, for size comparison, a conventional radio rectifier tube. The power supply in some models takes the form of a wind-driven generator; in others a small battery is used. A four-tube receiver is condensed into an extremely small space by a technique wherein the circuit elements such as resistors and capacitors are printed on or are made an integral part of a ceramic mounting base. The tubes, only $\frac{3}{8}$ inch in diameter and about 1 inch long, are soldered directly to the base. Four

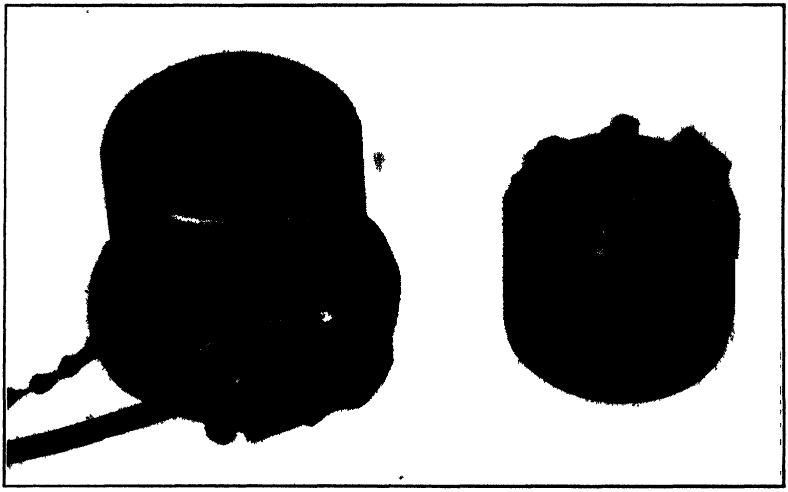


FIG 9–19 Exterior and interior views of a geophone used in geophysical explorations. *Courtesy Century Geophysical Corporation.*

successive steps in making a simple two-tube printed electronic circuit are illustrated in Fig. 9–18.

Mechanically excited shock echoes are used in seismic surveys to detect variations in the subsurface strata of the earth in connection with exploration for oil. In such a system a number of metal-enclosed dynamic microphones, such as the ones illustrated in Fig. 9–19 and termed geophones, are laid out on the ground surrounding a drilled hole in which a charge of dynamite is exploded. Waves from this artificial earthquake are reflected from the underground strata to the geophones on the surface, whence they are transmitted as electrical impulses to amplifiers located in an instrument truck. Suitable audio-frequency ampli-

fiers with adjustable band-pass filters, covering the range from about 20 to 80 cycles per second and connected to extremely rugged but sensitive galvanometers, are used to make recordings which may be studied and analyzed later. A typical seismic

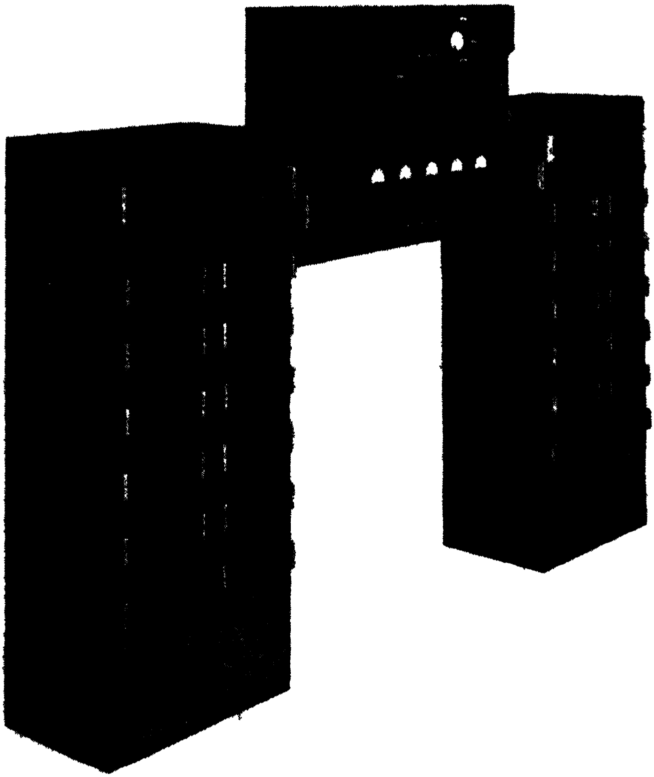


FIG. 9–20. Unitized seismic survey instrument assembly. *Courtesy Century Geophysical Corporation.*

survey instrument assembly, consisting of two banks of twelve amplifiers with power supplies and mixing panels, a master control panel, and the recording oscillograph, is shown in Fig. 9–20. From the recordings the trained geophysicist can determine the probable type of underground formation, and from the elapsed intervals he obtains information as to the exact depth at which

various formations will be found. Although it is true that seismic surveys do not indicate positively the presence of petroleum, they do provide a comparatively inexpensive and reliable means of mapping the subsurface strata and the locations where the formations of petroleum deposits are most probable.

Supersonic vibrations are sound waves having frequencies higher than about 15,000 cycles per second and hence are inaudible to the human ear. Although they were known to exist, supersonic vibrations of substantial magnitudes were first generated in 1925 by G. W. Pierce who used an oscillating quartz crystal to produce them in gases. In 1927 R. W. Wood and A. L. Loomis reported the generation of supersonic energy having a frequency of about 300 kilocycles per second in oil by energizing a piezoelectric quartz crystal at 50 kilovolts; they obtained pressures of about 150 grams, sufficient to elevate the free surface of the oil about 3½ inches. Since then many interesting applications of supersonic vibrations have been discovered and developed, such as the production, acceleration, and control of emulsification and homogenization; the detection of flaws and imperfections in solid structures, such as castings, rods, or strips; and underwater signaling, including echo depth soundings and explorations. Energy of the high-frequency vibrations may be concentrated in a very narrow beam by means of proper windows, lenses, and reflectors analogous to equivalent optical devices. Supersonic energy is transmitted and received by magnetostrictive, piezoelectric, or dynamic transducers; each has its particular sphere of application.

In the testing of solids for internal imperfections, supersonic vibrations having frequencies between 50 and 1000 kilocycles per second are commonly used, the optimum frequency being determined by the test material and the nature of the imperfections. The generator consists of an electron-tube oscillator connected to the transducer that applies the supersonic vibrations to the surface of the material under test. The vibrations are transmitted through the specimen and are received on a similar transducer located on the other side of the material. One transducer may be used for transmitting pulses and then receiving the reflected energy during the quiescent period between pulses. Density, or an apparent change in the modulus of elasticity, or both affect the transmission of supersonic energy through solid

material, and, since the effective modulus is small at a separation junction, cracks or separations as thin as 0.001 inch may be readily determined. Flaws in rods or strip stock are at times produced in the form of long pipes or pockets during rolling

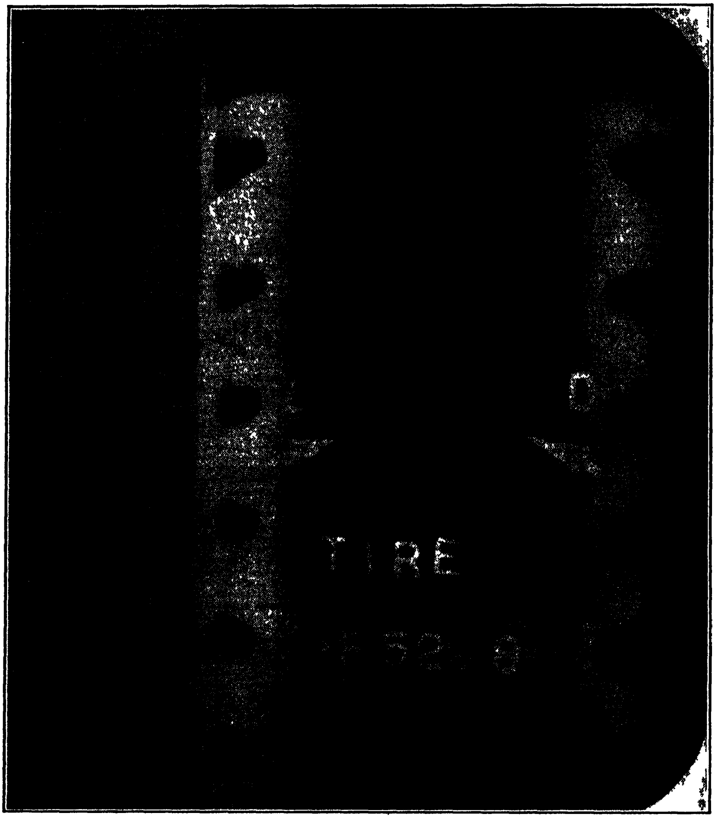


Fig. 9–21. Radiogram of an automobile tire does not show rubber separation from fabric, but a recording from a supersonic flaw detector indicates this defect. *Courtesy Brush Development Company.*

because of entrapped gases. The material may be tested by passing it through a liquid-filled tank with piezoelectric transducers mounted to face it at both sides. In automobile tires the rubber jacket occasionally separates from the rayon or cotton fabric, leaving a thin air pocket between them. As illustrated in Fig. 9–21, X rays do not detect flaws of this nature,

but, as indicated by the trace at the left of the figure, their presence may be easily detected by means of the meter reading in the output circuit of a supersonic flaw detector.

Underwater sound signals travel at the rate of 4800 feet per second plus or minus a small correction factor dependent on the temperature and the saline content of the water. The time interval between a supersonic pulse and the reception of its echo is a direct measure of the distance from the transmitter to the reflecting surface. Echo-type instruments are used for depth recording of water under a ship or for the exploration for schools of fish. Sound, navigation, and ranging (Sonar) is an important naval application of supersonic communication and exploration. Supersonic vibrations are preferred over audible frequencies for these purposes because (1) they are easily directed, (2) the equipment may be made responsive to only a narrow range of frequencies, and (3) their use prevents interference from extraneous audible sounds.

9-4. Navigational Aids

Radiobeacons and other radio aids to navigation have been developed as a public service. In the United States the Coast Guard has erected beacon transmitters, along the coastlines of the mainland and outlying territories, which operate continuously during fog or low visibility and during one or two 10-minute periods out of each hour in clear weather. Each station is assigned a definite frequency in the neighborhood of 300 kilocycles per second and also a certain code and transmission characteristic by which it can be recognized. The radio direction finder, as illustrated in Fig. 9-22, is a small compact superheterodyne radio receiver, tunable throughout a frequency range from 270 to 520 kilocycles per second and equipped with a rotatable shielded loop antenna. When the plane of the loop is placed at right angles to the line of direction between the vessel and the distant radiobeacon, the signal is zero or nearly so. This null position is the point at which a bearing is taken relative to the ship's bow, but in order to establish the location of the ship's position, or a fix, an additional reading is taken on another radiobeacon. The ground wave, which follows the earth's curvature, is the wave used for observing radio bearings; the sky wave at these frequencies is not dependable for radio bearings.

Radiobeacon transmitters have a reliable average range of 10, 20, or 100 miles, depending on their location and power. Nearly half of them are placed on lightships, and their signals provide a valuable navigational aid for ships in approaching coasts and ports.

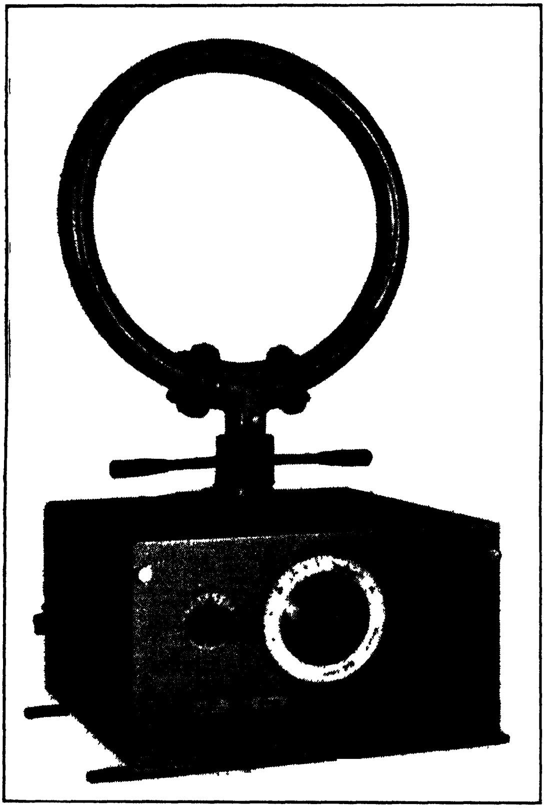


FIG. 9-22. Radio direction finder. *Courtesy Radiomarine Corporation of America.*

In transoceanic flying, occasions sometimes arise when an aircraft's position needs to be fixed quickly and accurately. For this purpose the Coast Guard has established a network of high-frequency direction-finder stations, interlinked by radio, telephone, and teletype. If an airplane over the ocean requests information on its location or reports itself in distress, all the control rooms of the direction-finder stations along the coast

are advised by teletype to take a bearing on the plane. Each individual bearing is relayed quickly to a plotting center; there the intersecting lines accurately locate the position of the airplane and information is transmitted to the plane; if necessary, task units are assigned to render aid. In general, the method of direction finding is similar to the one mentioned previously, except that high-frequency signals are employed and the locations of transmitter and receiver are reversed.

In 1927 the Department of Commerce began the installation of a network of radio transmitting stations at strategic points about 200 miles apart along airways to broadcast weather information and to provide radio beams as an aid to navigation for aircraft. Each transmitter broadcasts continuous signals by means of an antenna array consisting of either a pair of large crossed loops or four vertical radiators. The radiation pattern resembles a four-leafed clover and provides four equisignal courses of about 2° in width located between each pair of overlapping lobes. The radio-frequency carrier in two alternate lobes is continuously modulated with a tone signal comprising a dot and a dash, or *A*, while that in the other two lobes is modulated to produce a dash and a dot, or *N*. In the ideal case the two courses are at right angles to each other; the signal is transmitted so that true north always passes through an *N* quadrant except when the course is due north, at which time the *N* quadrants are located in the northwest and southeast. An aviator listening to the signals on a receiver hears a continuous tone if the aircraft is on the beam between the radiation pattern lobes, but this signal changes to the letter *A* or *N* when the aircraft deviates and signals are received from only one lobe of the transmission pattern. Courses at the transmitter may be shifted from right-angle positions by decreasing the amplitude of the current in one loop, and one or more courses may be bent by changing the phase relationships of the antenna currents. A similar technique is utilized where vertical radiators are employed. Each station transmits a designated group of call letters from time to time by means of which it can be identified.

A long-range navigation system, termed *loran*, has been developed. It permits a ship or an airplane to pinpoint its position accurately with respect to longitude and latitude over day-

time distances up to 700 miles and approximately twice that at night. This system consists of a number of pairs of pulse transmitters located on the coastline, and a receiver equipped with a suitable indicator located on the ship or aircraft. It depends for its operation on the constant velocity of transmitted radio signals, and, therefore, the distance between the transmitter and receiver is a direct measure of the time required from the transmission to the reception of the signal.

Two transmitting stations, one a master and the other a slave, are separated by several hundred miles, and they transmit pulses differing by a known interval at a constant repetition rate. The slave transmitter's signal is slightly delayed so that it will arrive after the master station signal at any given receiver. A loran navigator observes the time difference between received signals; it is equal to the transmitted time difference only if he is equidistant from the two stations. But if, for instance, the difference in time between received signals and the difference between transmitted pulses is 500 microseconds, the difference in the distances from the two points is represented by the distance a radio wave travels during that period, or about 93 miles.

Charts have been prepared showing equal time differences between the pulses received from a pair of loran stations; these lines are approximately spherical hyperbolas and would be plain hyperbolas, with the transmission stations at the focuses, if the earth were flat. Although the navigator knows that a definite time interval between the received pulses indicates his position as being on a specific hyperbola, his exact location is determined by making a similar observation on a second pair of stations. The intersection where the second line of position crosses the first gives the exact position or fix. Curves of this type are shown in Fig. 9–23, where a specific fix is indicated.

The interval between the received pulse signals from a pair of transmitters is determined by observing their traces on an oscilloscope. As indicated in the lower portion of Fig. 9–23, the pulse signals are alined onto conveniently displaced platforms, each on a horizontal sweep and one displaced above the other; the upper trace indicates the master station pulse and the lower trace indicates that from the slave station. Operation of a loran indicator depends on the superposition of the two received pulses, termed pips, after they have been made equal in ampli-

tude. During this alinement process the operator injects a delay into the equipment comparable to the difference of the arrival time of the two signals, and this interval is totalized from a

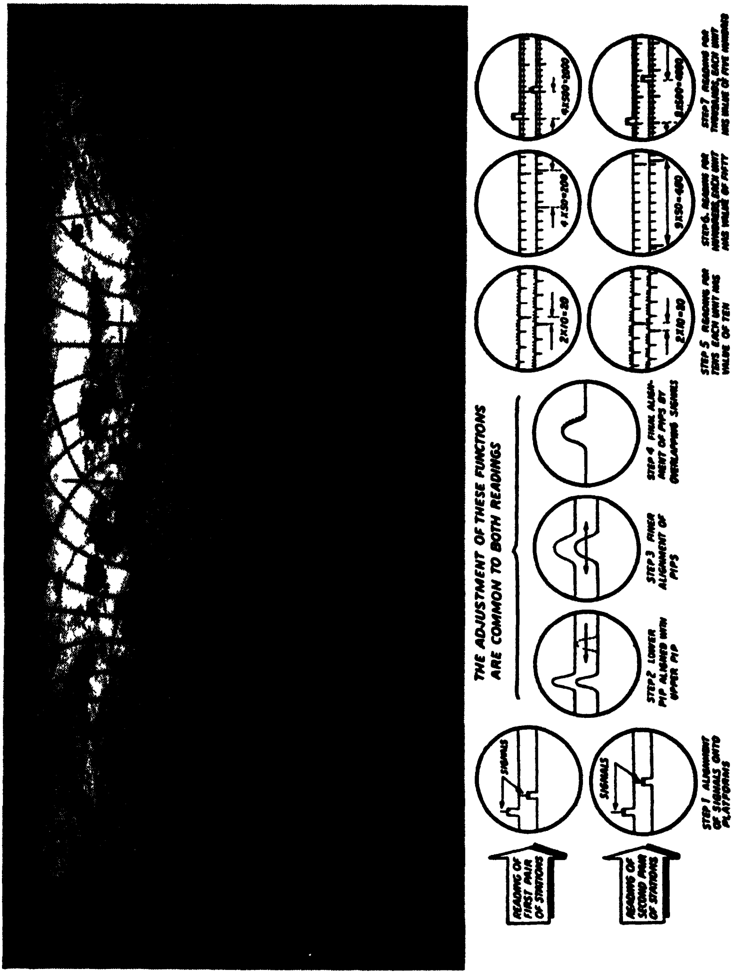


Fig. 9–23. Loran curves and oscilloscope reading indicating a navigational fix. *Courtesy United States Army Air Forces.*

family of marker pulses switched onto the traces after the receiver is disconnected. In order to complete the fix another observation is then made on a second pair of transmitters.

Present loran transmissions are conducted at frequencies in the neighborhood of 2 megacycles per second with an average

radiated pulse power of approximately 100 kilowatts. Slave stations transmit their pulses 20,000 microseconds later than those from the master stations. Since all loran transmitters pulse on the same frequency, station pairs are identified by their pulse rate, which varies from 20 to 33 per second. Loran receivers have consistently obtained fixes over water accurate to within a mile. At the end of 1945 more than 70 loran transmitters were in operation, affording navigational nighttime service over 0.3 of the earth's surface.

An important problem in aircraft navigation is that of landing a plane under adverse weather conditions when the visibility is poor. Many radio instrument landing aids have been proposed and devised, but basically there are two practical solutions to the problem; in many respects they are analogous to the two direction-finding systems. One solution is to place receiving and indicating equipment on the aircraft and under the control of the pilot, who makes the necessary observations and lands the craft accordingly. The other solution is to locate the observation equipment at or near the airport, where radar readings are made on an incoming aircraft, and to advise the pilot by two-way radio communication how to control the ship by instrument readings so as to achieve a proper landing. By either method the pilot is able to guide his plane to a position from 200 to as low as 50 feet above the end of the runway, from which point he completes his landing by visual means.

In the instrument landing system a group of four high-frequency radio beams are transmitted by stations located near the runway. These beams are modulated with constant-amplitude audio-frequency signals of 90 and 150 cycles per second and are transmitted to form an angle of a few degrees with the ground. The beams overlap to produce a tapering, pencil-like, glide path which extends in line with the runway for a distance of more than 10 miles. Radio marker beacons, designed to radiate energy in a vertical direction, are located at various points along the glide path to give the pilot a check on his position. A chart of a portion of the Department of Commerce, Civil Aeronautics Administration, instrument landing system approach control at the Indianapolis, Indiana, airport is shown in Fig. 9–24. The antenna array for the localizer, which supplies the glide path for that installation, is illustrated in Fig. 9–25. Two

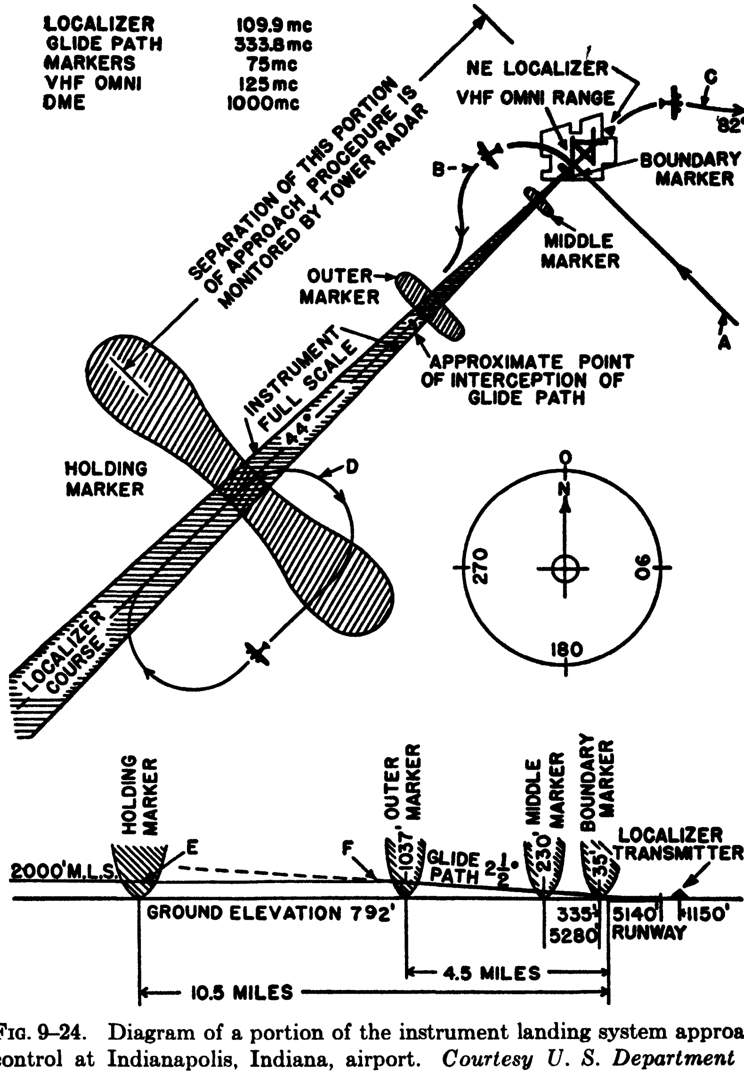


Fig. 9–24. Diagram of a portion of the instrument landing system approach control at Indianapolis, Indiana, airport. *Courtesy U. S. Department of Commerce, Civil Aeronautics Administration.*

crossed pointers in an indicator located on the instrument panel of an incoming airplane are actuated by the received signal and inform the pilot whether the aircraft is to the right or the left of the beam or above or below it. A voice channel may also be utilized in connection with the radio-frequency beam in order

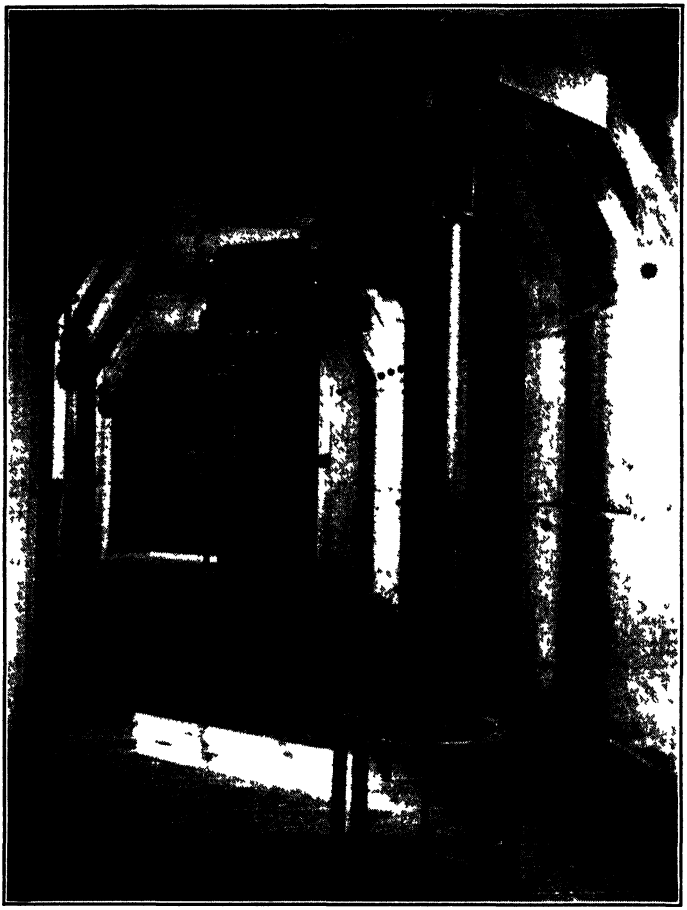


FIG. 9–25. The 8-loop localizer antenna array mounted on pipe pedestals above a metal counterpoise and located in a wooden shelter Indianapolis airport installation *Courtesy U S Department of Commerce, Civil Aeronautics Administration*

to permit radiotelephone contacts with a pilot before or during an approach. To prevent interference with the control signals, both transmitting and receiving equipment for voice is designed to have a low-frequency response limit of about 200 cycles per second.

Figure 9–24 also shows the transmitters of the omnirange, an improvement on the four-course range described earlier in this

section. This new navigational aid offers an almost unlimited number of ranges or paths for aircraft, and since the system operates in the very high frequency portion of the radio spectrum, the received signals are less subject to static and other interference. Each omnirange is provided with a distance measuring equipment (DME) by means of which the pilot determines his exact distance to the omnirange transmitter. The pilot, therefore, needs only to observe the dial readings on two instruments to determine his exact position.

The ground-controlled approach system is based on radar technique, whereby a ground station operator follows the movements of an airplane on two oscilloscope screens. One of these shows the general position of the incoming plane as a moving spot of light, and by noting the movement of the spot as it moves across the screen the operator can advise the pilot how to direct his course to reach the airport. After the plane approaches the immediate vicinity of the landing field, the operator switches to the other oscilloscope, which gives a detailed indication of the plane's altitude and direction in relation to the runway. The ground operator follows the spot of light on this oscilloscope, directs the pilot to make any necessary changes in altitude and direction, and guides him safely down until the pilot is able to take over the actual landing by visual means.

Problems

1. Trace the input and output circuits of the two-wire telephone repeater, Fig. 9–1, with respect to coupling between the two tubes. Why are oscillations not produced under normal operating conditions?

2. Make a list of the circuit elements of the five-tube radiobroadcast receiver, shown in Fig. 9–7, which contribute toward automatic volume control, and define their function.

3. Redraw the block diagram of the television receiver, Fig. 9–12, and from your knowledge of the functional operation of each block, draw on the connecting lines a few representative voltage cycles, such as might be observed on an oscilloscope connected to the input terminals of each block. The discriminator separates audio frequencies from the radio-frequency carrier and the sync separator converts square-wave voltage pulses to sawtooth waveforms.

4. Review the proper references listed at the end of this chapter or consult other references on Sonar, and make a report on the construction, operation, and frequency response of the magnetostriction transducer when used as a sound projector.

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10 ·

Electronic Controls

The previously discussed automatic pilot, photoelectric register regulator, and proximity fuze depend for their operation on electronic controls, a field of great potentialities. Innumerable operations and processes, ranging from a simple circuit closure that opens a door to the guiding from take-off to landing of a robot ocean crossing of a pilotless transport airplane, utilize electronic devices to perform assigned tasks that are impossible to achieve with other apparatus, or they do them more simply or more economically than other means. In this chapter we shall review some additional control adaptations and briefly survey electron-tube applications in motor speed control and electric welding, two factors that play no small part in maintaining America's pre-eminence in industrial production.

10–1. Control Fundamentals

Control, in its simplest form, opens or closes an electric circuit. For instance, a conveyor line is made to stop when the product to be packaged is missing or displaced from its proper position as indicated by the light received on a phototube. This basic on-and-off control is also applied to thermal problems, in which an electric circuit is closed in response to a demand for more heat or for more refrigeration and is subsequently opened when the desired temperature has again been restored. Similar applications exist in chemical engineering, when, during the production of raw sugar, lime water is added to the clarified sugar-cane juice to change it from a slightly acid to an alkaline solution in order to prevent inversion of the sucrose to dextrose. In

these examples the controlling action is intermittent, and overshooting occurs if the process demands very close control and if there are process delays and lags, such as a distance-velocity lag for temperature variations or a chemical reaction lag for *p*H changes. Overshooting may be eliminated or reduced by the use of a wide range of process control, that is, with a large dead zone. But many processes must be controlled very accurately, and control methods have been devised that operate on the basis of supplying the corrective condition for a group of longer or shorter intervals, depending on the extent of the deviation from the normal. The deviation detection element makes continuous observations and relays the extent of the demand back to the correction device. Depending on the nature of the process and the permissible deviation, corrective measures are applied which vary as the displacement from the normal plus a correction factor that varies as the first derivative or velocity of the change. Moreover, a second derivative or acceleration control factor is added if control requirements are still more stringent. Fortunately, many industrial processes do not require such fine control.

Electronic control equipment of the on-and-off type is exemplified by the bean-sorting machines illustrated in Fig. 10–1. In a Michigan plant 100 photoelectric units sort 80,000 pounds of beans a day. Beans to be inspected and sorted are fed into a hopper, beneath which there is a drum. A suction arrangement, through tiny apertures, holds the beans around the drum circumference, and the drum carries them around to the photoelectric equipment. On the way to the phototube, a mechanical patter adjusts the beans to a proper position for inspection. A white bean is permitted to proceed, but when a dark or discolored bean passes before the phototube, the reflected light is less than before, a tripper is energized, and a metal finger flicks the defective bean into a reject chute.

Wire-drawing machinery, weaving machines, and printing presses driven by a-c motors require accurately controlled applied torque during acceleration to prevent whiplash effect and subsequent breakage of the wire strands, thread, or paper. Conveyor drives, cranes, and hoists operate over wide climatic and load conditions. On hot summer days, for example, the pulleys of an outdoor belt conveyor on the coal dock of a power generat-

ing station rotate freely in their bearings, whereas the stiff grease, when first starting up on cold mornings, offers an additional load, causing the motor to require a longer time to accelerate to full speed. When fully loaded, the starting time is still further increased, and attempts to expedite starting only cause spinning of the driving head pulley, which burns the belt. Clearly, some method of control that automatically accelerates the motor in



FIG. 10–1. View of a group of photoelectrically operated bean-sorting machines. *Courtesy General Electric Company.*

the shortest time with due regard to the load and a predetermined maximum motor torque is indicated. One of these methods utilizes an a-c wound-rotor motor with a starter that interprets each of these conditions with the aid of an electronic circuit composed of two major elements: a time element and a current element. As shown in the circuit, Fig. 10–2, the time element, based on the principle of the time required to charge a capacitor, receives its energy from the line. The current element, which operates on the same principle, is energized by the motor current and is connected in opposition to the time element. With a light load the starting current is low, and the current element has little effect on the time element. A larger load increases the motor current, and the current element opposes the charging

of capacitor C_3, automatically lengthening the time between starting steps. Time and current adjustments for proper starting are preset by adjusting the time potentiometer P_1 and the current potentiometer P_2. Transformer T_1 is a potential transformer, and T_2 is a current transformer. The gaseous rectifier tubes V_1 and V_2 are of the cold-cathode type and require no fila-

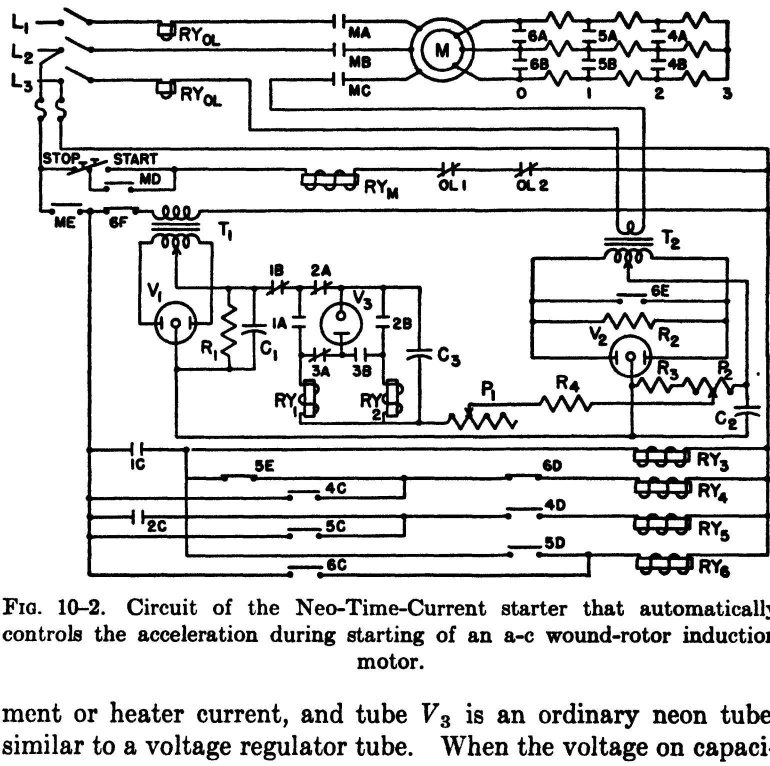


FIG. 10–2. Circuit of the Neo-Time-Current starter that automatically controls the acceleration during starting of an a-c wound-rotor induction motor.

ment or heater current, and tube V_3 is an ordinary neon tube, similar to a voltage regulator tube. When the voltage on capacitor C_3 reaches a predetermined value, it discharges through tube V_3 and energizes relays RY_1 and RY_2. Figure 10–3 illustrates the control unit and shows the three relays RY_1, RY_2, and RY_3. Relay contactors RY_4, RY_5, and RY_6 (which close the contacts on the accelerating resistances in the rotor circuit of the motor), as well as the overload relays, the main line switch, and the main circuit contactors M, are located on the main panel shown in Fig. 10–4.

Operation of the starter may be illustrated by its use on an ore crusher. The starter is adjusted to allow 125 per cent torque

on the first point with contacts 5A and 5B closed, approximately 200 per cent on the second point with contacts 4A and 4B closed, and a torque of nearly 275 per cent with the maximum resistance in the rotor circuit. If the crusher is loaded with ore, the motor

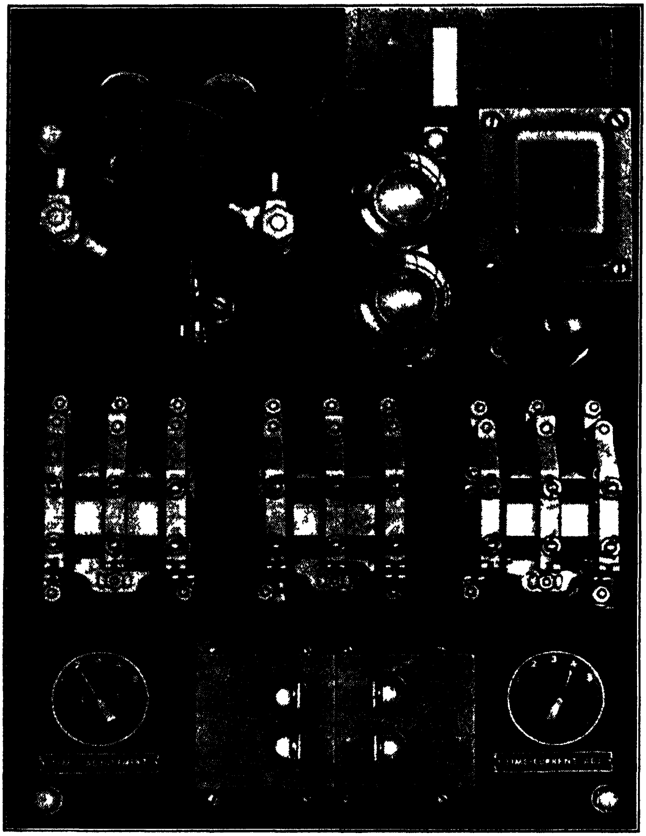


FIG. 10-3. Control unit for the Neo-Time-Current motor starter. *Courtesy Electric Controller & Manufacturing Company*

will fail to start on the first and possibly on the second point. On the third point, the motor will start, but a long accelerating time must be provided; otherwise the early closure of the next group of contacts reduces the torque and may stall the motor. As the motor accelerates, the torque requirements become less, and when the line current drops to the preset value the contacts close, reducing the resistance in series with the rotor winding.

Should the crusher be jammed so that the motor cannot accelerate its load on the third point, the next group of accelerator contacts will not close. The control then locks out on this point,

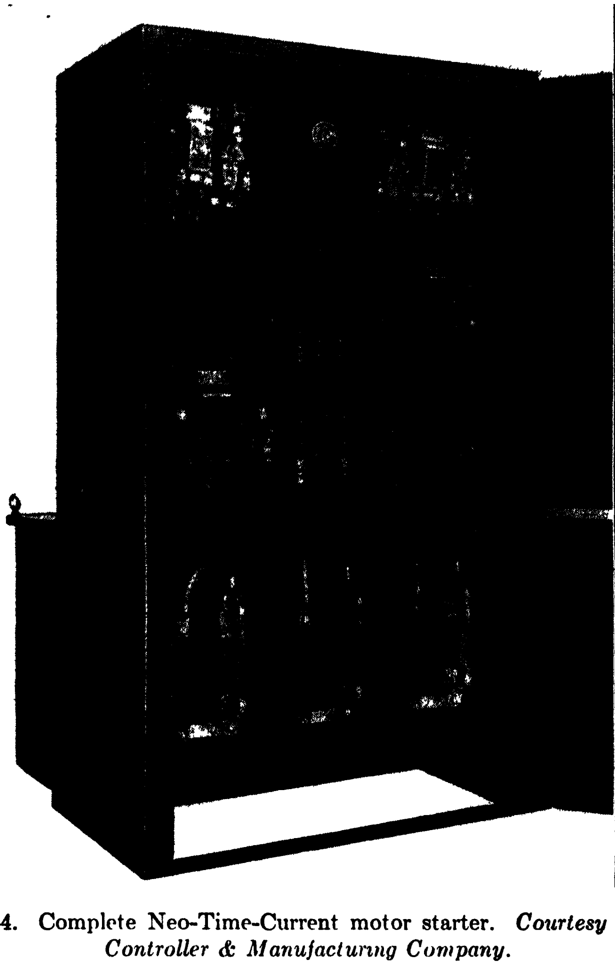


FIG. 10-4. Complete Neo-Time-Current motor starter. *Courtesy Electric Controller & Manufacturing Company.*

since further reduction in rotor resistance only results in a greater current with reduced motor torque, and the overload relays operate to disconnect power from the motor.

Thyratrons are commonly employed to obtain continuous variation of control throughout a given range; frequently they are used in conjunction with saturable reactors in a-c circuits to

control resistive loads. Decorative lighting control for theaters and auditoriums, of which the installation in 1929 at the Chicago Civic Opera House was one of the earliest, is of that type. It provides control for 160 lighting circuits, each of which may require up to several kilowatts of lighting load. The control board in such installations can be located at a convenient place where the operator can view the colors as they change and blend, and the control equipment with the reactors can be located in a remote place, such as a basement room. Complete scenes with

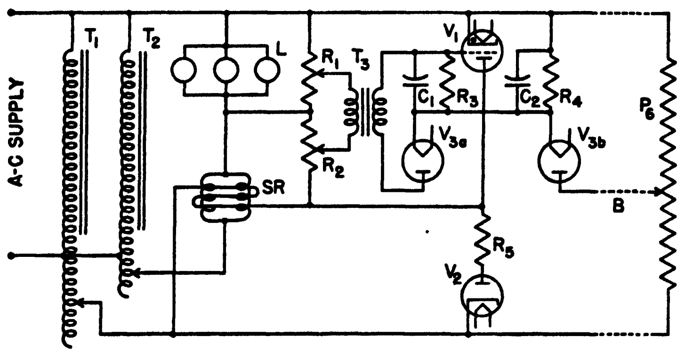


FIG. 10–5. Simplified lighting control circuit that uses a thyratron and a saturable reactor.

preset light intensities may be set up as desired, and later with the closure of a switch a smooth transition of light of two or more colors from one scene to the next takes place at a controlled rate. A simplified single circuit for lighting control is given in Fig. 10–5. Two autotransformers T_1 and T_2 provide the proper voltages for the control and load circuits respectively. The lamp load is connected in series with the a-c winding of a saturable reactor *SR*. Thyratron V_1 supplies the d-c winding of the reactor, and the gaseous rectifier V_2, in series with a low-valued resistor R_5, is connected across the coil. During that portion of the a-c cycle when tube V_1 does not conduct, the stored energy, due to the direct current in the reactor winding, permits the induced voltage during the collapse of the field to continue the current flow in the same direction, using tube V_2 and resistor R_5 as a return path, and so maintains the direct current at a nearly constant value.

The average magnitude of the current through thyratron V_1

is determined by its grid potential, which, in turn, depends on an initiating alternating voltage arriving on the B wire which is connected to the anode of rectifier tube V_{3b}. This B wire derives its voltage difference to the junction of resistor R_4 in complex lighting systems from regulated and preset master circuits; in simple installations the voltage difference is obtained from a potentiometer P_6, connected across the line as indicated in the figure. The time constant of the C_2R_4 combination in the cathode circuit of tube V_{3b} is arranged to be long so that the constant d-c capacitor voltage is practically equal to the value of the peak voltage on the B wire. This direct voltage is also impressed on the grid circuit of thyratron V_1. However, the secondary winding of transformer T_3 is connected in series with the rectifier tube V_{3a} and the load composed of the resistor R_3 and capacitor C_1. The last two have a much shorter time constant than C_2R_4. The primary winding of transformer T_3 derives its excitation from taps on the two potentiometers R_1 and R_2; the voltage limits and the control curve vary with the slider positions, but usually the excitation is obtained with the sliders connected across the load. With the secondary winding of transformer T_3 phased so that tube V_{3a} conducts on the alternation when the thyratron V_1 is inoperative, the feedback voltage places an opposition direct voltage across R_3, resulting in an over-all grid voltage on tube V_1 which may be nearly zero, allowing the thyratron to conduct throughout the entire ensuing half cycle. When the feedback transformer derives its excitation from a voltage equivalent to that existing across a portion of the load, the final load voltage is greater than, but proportional to, the initiating voltage on the B wire. The combination of the two opposing voltages in the grid circuit of thyratron V_1 may be varied over wide limits, resulting in a wide variation of the alternating voltage impressed on the load. Figure 10–6 illustrates the lighting control panels installed at Radio City Music Hall. Control is provided for 314 lighting circuits and for five preset scenes in advance of the scene undergoing presentation. As much as 16 kilowatts of lighting load per circuit may be controlled and made to change almost imperceptibly by extremely small amounts of controlling energy from the control board located just back of the orchestra pit.

It is not always expedient for the accurate control of a quantity subject to a disturbance to apply corrective measures directly;

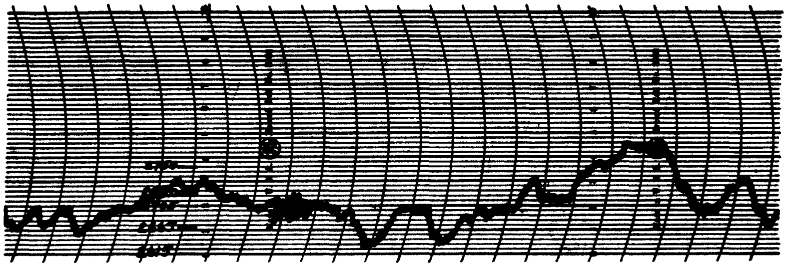
frequently a roundabout method of control is just as effective. For instance, a constant temperature may be maintained in a cement kiln by changing the fuel feed as required or, as an alternative solution, by changing the speed of the kiln. In either



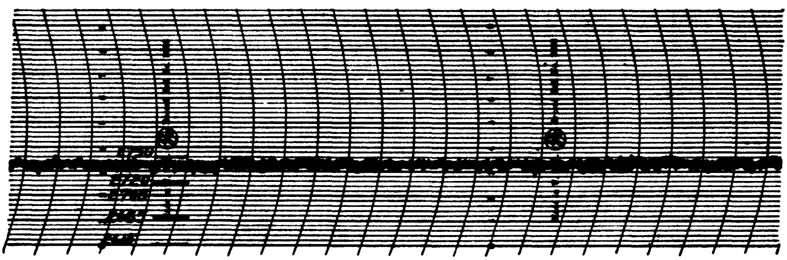
FIG. 10–6 Thyratron-reactor group for the lighting control in Radio City Music Hall, New York City. *Courtesy General Electric Company.*

method one of the major problems concerns itself with thermal lag within the kiln. For the error-detecting device, highly satisfactory results have been obtained in measuring the temperature of cement clinker by means of a photoelectric pyrometer, and also in controlling the kiln operation automatically in accordance with the indicated temperature. Control is effected by the photoelectric circuit acting on thyratrons that cause contactors to operate, which in turn, as illustrative of the indirect method,

control a small motor that changes the position of the brushes on an a-c brush-shifting adjustable-speed motor. When the temperature within the kiln starts to increase, the control causes the rotating speed of the kiln to increase, resulting in a higher rate of movement of the cement clinker through the clinkering zone and producing a decrease in the temperature of the clinker. An



(*a*)



(*b*)

FIG. 10–7. Photoelectric pyrometer charts of the cement clinker temperature in degrees Fahrenheit. (*a*) Manual control of kiln speed; (*b*) automatic control by photoelectric pyrometer. *Courtesy General Electric Company.*

antihunting circuit is used in the input circuit of the thyratrons. The effectiveness of this control is shown by the curves in Fig. 10–7. Aside from achieving a more uniform product, such a system of control results in an appreciable reduction in kiln fuel.

10–2. Voltage and Speed Regulators

Electromechanical methods of maintaining a constant generator voltage in power-plant operation by the change of resistance in series with the exciter field winding are not new; they have been used for many years. Inherently, such methods suffer

from a number of limitations: the bearings and vibrating contacts require much servicing and frequent replacement; the inertia of the mechanical parts introduces an objectionable time lag; a large dead zone is inevitable in order to overcome the friction of mechanical regulators; and costly or elaborate apparatus must be installed if the previously mentioned disadvantages are to be minimized. Electronic controls, on the other hand, overcome these objections and provide a reliable, simple, static, and relatively inexpensive control mechanism.

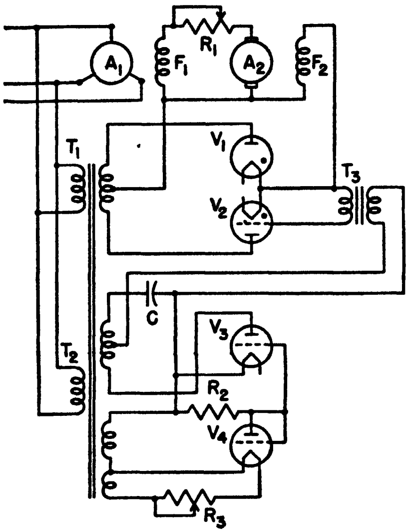


FIG. 10-8. Simplified circuit of an alternator voltage regulator.

A simplified circuit of a voltage regulator is shown in Fig. 10-8. The a-c generator armature is represented by A_1, the generator field by F_1, and the field rheostat by R_1. The field is excited by a d-c exciter, the armature being designated by A_2 and the exciter field by F_2. Two gaseous tubes, a rectifier tube V_1 and a thyratron V_2, supply and control the d-c exciter field excitation. Some features of the exciter field-control circuit are of interest and will be considered in detail. Control transformer T_2 supplies the filament of the rectifier tube V_4 through the control rheostat R_3, the tube being operated under conditions of voltage saturation. A slight change in the a-c line voltage causes a marked change in the cathode temperature and a relatively large change in the anode current of the tube. Load resistor R_2 in the anode circuit of tube V_4 is also located in the grid circuit of tube V_3, where the varying voltage drop across the resistor affects the conductivity of that tube and in effect makes it a variable resistor. It is connected in series with capacitor C across the upper secondary winding of control transformer T_2. Capacitor C and tube V_3, together with the transformer winding, act as a phase-shifting device, causing the phase relationship of

the voltage to vary as the resistance of tube V_3 changes. The phase-controlled voltage is impressed on the primary winding of a grid transformer T_3, and the secondary voltage controls the breakdown point of the grid-controlled rectifier V_2. Anode circuits of tubes V_1 and V_2 are supplied by transformer T_1, and the load consists of the d-c exciter field F_2. Tube V_1 is not grid-controlled; nevertheless, changing the resistance of tube V_3 and modifying the control of thyratron V_2 adjust the output current of both tubes V_1 and V_2. This common adjustment is due to the electromagnetic coupling of the two tubes provided by the high inductance of their combined load, which is the field winding of the exciter.

Operation of a typical regulating cycle involves the following steps on the assumption that the a-c generator load is decreasing, causing its voltage to increase slightly. This change increases the voltage and temperature of the cathode of tube V_4, producing an increase in its anode current and a correspondingly increased voltage drop across resistor R_2. The negative voltage on the grid of tube V_3, which is the voltage drop across R_2, increases, with the result that the anode current of tube V_3 reduces, thereby increasing the resistance of the tube. This causes the phase of the grid voltage of tube V_2 to be altered to decrease the output of both tubes V_2 and V_1, and the field current of the exciter is reduced. With the lowered armature voltage of the exciter, the a-c generator field current is decreased, and the terminal voltage of the a-c generator is returned to normal. Under increasing load the action of the circuit is reversed. The regulator is equipped with antihunting circuits and automatic protective features, but these are not shown in the circuit.

Figure 10–9 illustrates this voltage regulator. It constantly maintains the a-c generator voltage within a band of plus or minus 1 per cent of normal for all load conditions to full rated kilovolt-amperes. Corrective action starts within one-half cycle, that is, within $\frac{1}{120}$ second, of the slightest change in generator voltage. The voltage is returned to the normal band within $1\frac{1}{2}$ seconds after sudden load changes up to 50 per cent of the rated generator kilovolt-amperes, provided the speed regulation of the prime mover is kept within 5 per cent and the time constant of the exciter-generator combination does not exceed 3 seconds.

The speed of a machine driven by a d-c motor can also be held

constant within a fraction of 1 per cent and so regulated that it operates at a given speed and later at a different predetermined speed. Motor-speed regulators find application, for example, in

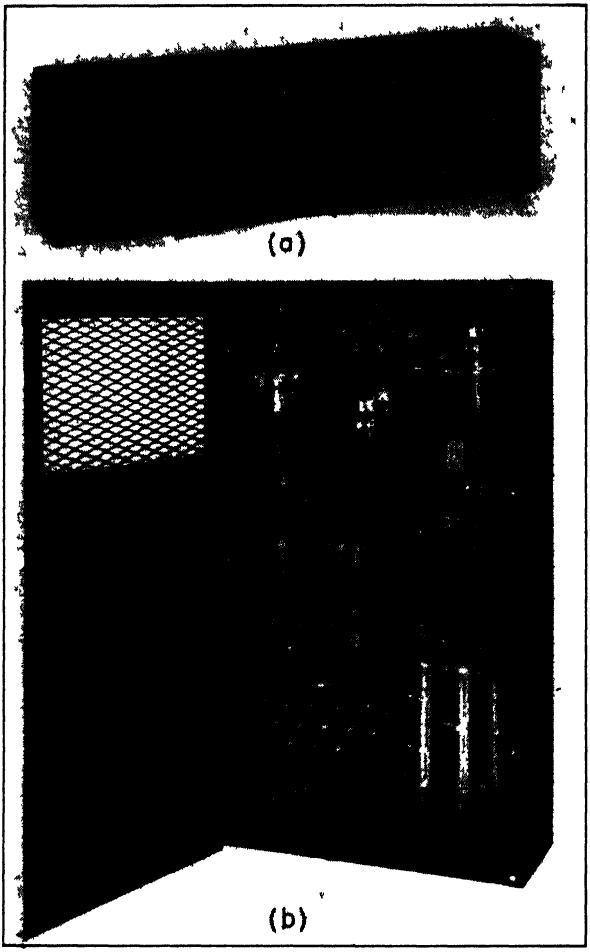


FIG. 10–9. Alternator voltage regulator (*a*) Control unit; (*b*) regulator unit. *Courtesy Ward Leonard Electric Company*

paper mills on single motor drives where the motor speed must be adjustable but must remain constant at all loads in order to process various kinds of paper. The circuit diagram of such a regulator is shown in Fig. 10–10. It operates on the principle of

changing the current through the field F_1 of an exciter E, which supplies a control field F_2 of a generator driven by a prime mover PM. The generator armature G delivers its output to the separately excited motor M, the speed of which is to be controlled. A separately excited d-c pilot generator PG, driven by the motor, generates a voltage directly proportional to the speed of the motor and, similar to an electric tachometer, provides an accurate indication of motor speed; it generates the voltage that actuates the regulator.

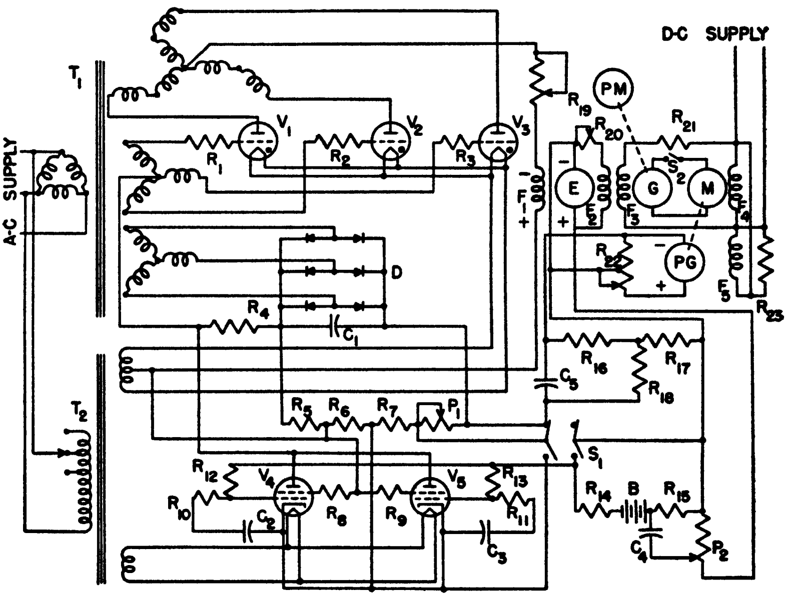


FIG. 10–10. Simplified circuit of a speed regulator for a d-c motor.

Three thyratrons, V_1, V_2, and V_3, connected as a three-phase half-wave rectifier, supply the direct current for the exciter field. The thyratrons are controlled by the sum of two grid voltages: a constant alternating voltage obtained from a quadrature phase-shift circuit, and a direct voltage, which varies in accordance with the deviation of the motor speed from a preset normal value and which is derived from the two amplifier tubes V_4 and V_5. The three-phase secondary windings supplying the thyratron anodes are connected in zigzag, and the three-phase secondary windings supplying the grids are phased and connected so that

the phase difference between the anode and the grid voltage on any given thyratron is 90°, with the grid voltage lagging the anode voltage. Another group of secondary windings on transformer T_1 supplies a three-phase full-wave copper oxide rectifier which delivers a constant direct voltage across the resistance network R_5, R_6, R_7, and P_1 for the proper direct voltages required by tubes V_4 and V_5. These two amplifier tubes are connected in parallel for reliability of operation. The grid-control circuit may be traced from the common cathode lead through resistor R_7, through resistor R_{22}, connected across the pilot-generator armature, and through the 45-volt battery B to each of the amplifier grids. The anode circuit connects to the neutral point of the transformer winding supplying the thyratron grids and returns through the center tap of the filament winding, through resistor R_6, to the amplifier cathodes. The controlling grid voltage that causes the thyratrons to fire earlier or later is determined by the direct voltage drop across resistors R_4 and R_5. Battery B acts as a reference standard and is connected so as to oppose a portion of the pilot-generator voltage, depending on the setting of resistor R_{22} and the desired motor speed.

Assuming that the motor speed decreases from the desired normal value, the voltage of the pilot generator decreases and the resultant voltage between the grids and cathodes of the amplifier tubes also decreases. This increased negative grid voltage reduces the current through the tubes, causing the current through R_4 to decrease, producing a more positive thyratron grid voltage, and permitting the thyratrons to fire earlier in the cycle to increase the exciter field current. An increase in motor speed produces the opposite of these results. Resistor R_{15} and capacitor C_4 prevent hunting in the amplifier control grid circuit; a similar stabilizing circuit is connected across the pilot-generator output. High-frequency hunting is prevented by the use of damping circuits C_2R_{10} and C_3R_{11}, connected from the grids to the cathodes of amplifier tubes V_4 and V_5.

Figure 10–11 illustrates the speed regulator, which is usually mounted on the front of the control switchboard. The speed-regulating potentiometer is located at the left, and the antihunting potentiometer on the right. A voltmeter, equipped with a plug, and jacks, connected to various points in the circuit, permit convenient checking of the circuit. Although a device of this

type can control the largest motors by utilizing a prime mover, such as a turbine, to drive the generator, ordinary installations generally employ an electric motor for that purpose in a conventional Ward-Leonard motor-generator unit. This control can



FIG. 10–11. Front view of the speed regulator for a d-c motor. *Courtesy Westinghouse Electric Corporation.*

also be applied with slight circuit changes as a voltage regulator on d-c generators, operating directly on the shunt field for the smaller sizes and on the exciter field for larger generators.

10–3. Adjustable-speed Motor Drives

The advantages of accurate speed control of d-c motors have long been recognized in the machine-tool industry. By holding the field voltage constant at its normal value and varying the armature voltage, but supplying the armature with rated full load current, smooth and stepless speed control can be obtained from a few revolutions per minute to the base speed of the motor, that is, a speed range of at least 20 to 1. Throughout this range

the motor delivers rated torque and a horsepower output which is directly proportional to the speed with rated power output at base speed. For speeds higher than the base speed the motor field is weakened; this provides an additional speed range of 2 or 3 to 1 above base speed, depending on the electrical and mechanical limitations of the motor. For the latter speed range, the horsepower output remains constant and the torque varies

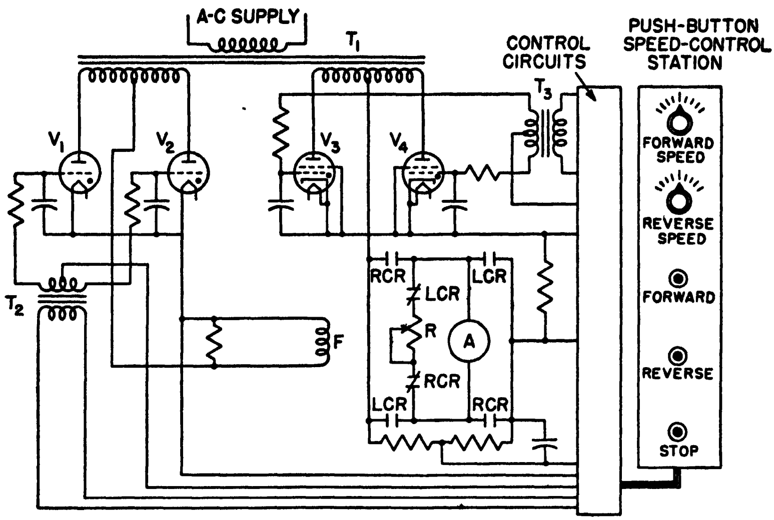


FIG. 10–12. Simplified schematic diagram of the Mototrol, the Westinghouse Electric Corporation motor speed control system.

inversely with the motor speed. Thyratrons and ignitrons are efficient rectifiers, and vacuum tubes are excellent control devices; by their means d-c motors are able to operate from ordinary a-c power lines with the speed controlled to meet the most exacting demands. Many electronic motor-control installations have been made since the first application to constant-tension wire reeling in 1928.

Figure 10–12 shows a simplified diagram of the Westinghouse *Mototrol* power circuit and indicates the control circuits and the push-button speed-control station of an adjustable-speed motor drive. Thyratrons V_1 and V_2, connected as a full-wave rectifier supply current to the field winding F of the motor, and thyratrons V_3 and V_4 supply current to the motor armature A through a

reversing contactor, designated as *RCR* and *LCR*. The output of these power supplies may be varied, each independently of the other, by a suitable shifting of the firing point of the thyratrons by a group of control tubes. Speed of the motor may be changed by adjusting a small tandem-type potentiometer arranged so that it can control the full range of armature- and

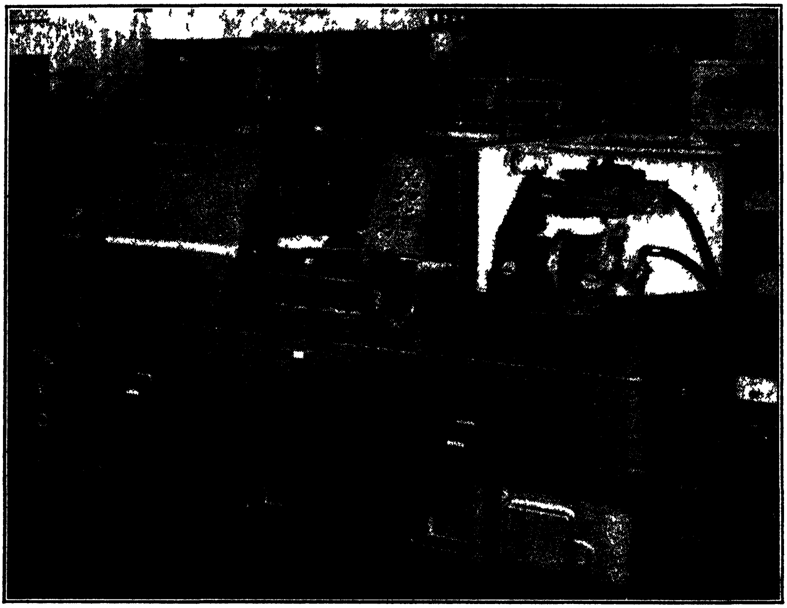


FIG 10–13 A Mototrol-equipped miller that machines fins on aviation engine cylinder heads *Courtesy Westinghouse Electric Corporation.*

field-current adjustment on one dial. The required grid potential for firing either pair of thyratrons consists of a combination of alternating and direct voltages. Depending on the setting of the control dial, a direct voltage is connected in series with the grid circuits of tubes V_1 and V_2 through the center tap of the secondary winding of transformer T_2, while the grids of thyratrons V_3 and V_4 are similarly supplied with a control voltage in series with the center tap connection on transformer T_3. Automatic current limit and time-delay acceleration are included, and, by pressing the proper pushbutton, the motor is smoothly accelerated to the operating speed corresponding to the setting of the speed-control potentiometer.

The motor is always started with full-field excitation regardless of the setting of the speed-control potentiometer. It can be quickly stopped by dynamic braking, achieved by the automatic connection of resistor *R* across the armature; the intensity of braking is adjusted by changing the value of the resistor. In addition, the rectifiers are automatically adjusted, as required, to compensate for loading or *IR* drop in the armature by responding to a voltage proportional to that across the armature and to

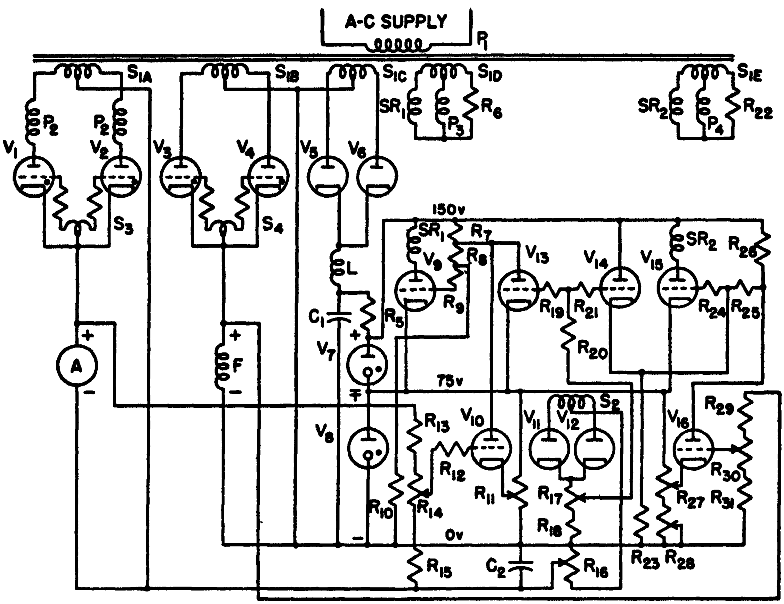


FIG. 10–14. Basic circuit of the Thymotrol, the General Electric Company motor-speed control system.

a voltage obtained from the secondary winding of a current transformer connected in series with the armature supply. By maintaining a constant load on the motor through speed control, increased production can be obtained from machine tools, and at the same time cutter damage is reduced to a minimum. A Mototrol-equipped fin miller, Fig. 10–13, which machines cooling fins on the cylinder heads of aviation engines, has its use factor increased as much as 30 per cent by speeding up the feed speed over the no-load section and reducing the speed to the proper value when the milling tool engages metal.

A simplified circuit of the General Electric motor speed-control system, termed *Thymotrol,* is shown in Fig. 10–14, and a Thymotrol installation is illustrated in Fig. 10–15. The system con-

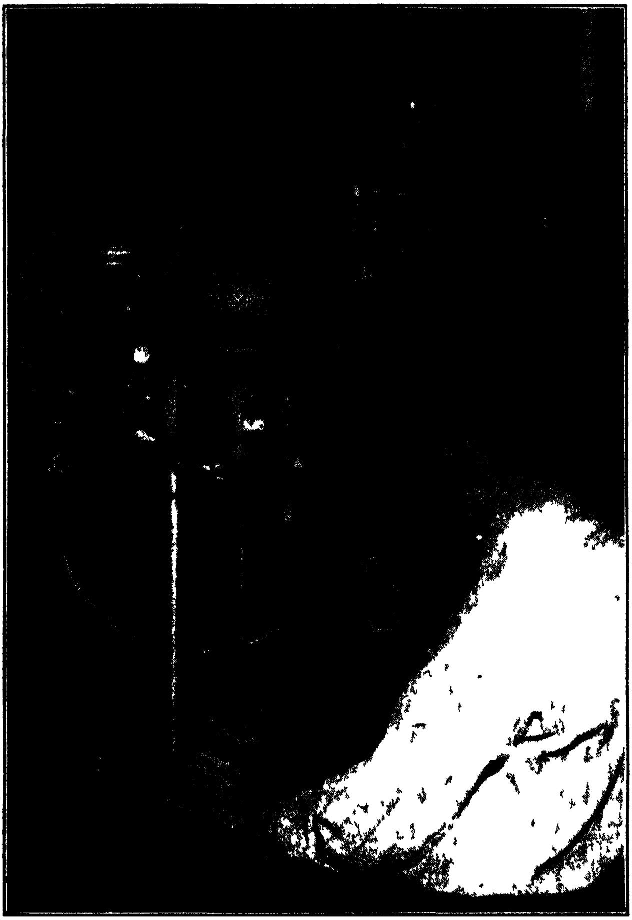


FIG. 10–15. Drill press equipped with a Thymotrol system on a 0.33-horsepower motor. *Courtesy General Electric Company.*

sists of a power transformer, a full-wave armature-current rectifier using thyratrons V_1 and V_2, a similar field-current rectifier using thyratrons V_3 and V_4, a control circuit, and a control panel. Firing of both pairs of thyratrons is controlled by shifting the phase of the grid voltage, which is derived from an induced

voltage in the center-tapped secondary windings S_3 and S_4, energized by primary windings P_3 and P_4 in the saturable-reactor bridge circuits. Control depends on advancing the firing point of the thyratrons by increasing the current through the d-c winding on each saturable reactor.

A full-wave rectifier circuit, consisting of tubes V_5 and V_6, filter LC_1, and voltage regulator tubes V_7 and V_8, supplies the d-c requirements of the control circuit. The potential across the regulator tube V_8 also serves as a reference voltage. The saturable reactor SR_1, responsible for the control of the armature current, derives its d-c excitation from tube V_9, the anode current of which is controlled by tube V_{10}. The potential of the cathode of tube V_{10} is predetermined by the position of the slider arm on potentiometer R_{11}, while its grid is connected to the slider arm on potentiometer R_{14}, which is connected in series with resistors R_{13} and R_{15} as a potential divider across the armature of the motor; the grid circuit finds its return through the adjustable resistor R_{16}. The anode of tube V_{10} is supplied through resistor R_7 from the regulated power supply, and, consequently, the voltage drop across R_7, for example, increases as the anode current increases. This is brought about by a less negative grid voltage caused by an increase of armature voltage across the voltage divider. The greater voltage drop across R_7 makes the grid of tube V_9 more negative, with the result that its anode current (the d-c current through SR_1) decreases, and thyratrons V_1 and V_2 fire later, regulating the armature voltage and the motor speed at a value determined by the dial settings on potentiometers R_{11} and R_{14}. The voltage or *IR* drop in the armature, however, changes with the load, and the voltage across the armature terminals includes the *IR* drop. In order to maintain constant speed irrespective of load, a voltage proportional to the load must be subtracted from the original control voltage.

Compensation for *IR* drop is effected by means of a current transformer composed of the primary windings P_2 in the anode circuits of tubes V_1 and V_2 and the center-tapped secondary winding S_2 which supplies the anode voltage for rectifier tubes V_{11} and V_{12}. Resistors R_{16}, R_{17}, and R_{18} constitute the rectifier load. The voltage drop across the adjustable resistor R_{16}, which is proportional to the armature current, is also connected in series with the grid circuit of tube V_{10} and causes that

tube to respond to a variation of grid voltage depending on the armature terminal voltage less its IR drop. A change in the adjustment of the slider arm of resistor R_{16} gives a rising or falling load-speed characteristic to the motor.

Tube V_{15} supplies the direct current for the saturable reactor SR_2 in the circuit that determines the firing position of thyratrons V_3 and V_4. The control circuit is in general similar to the armature-control circuit. Resistors R_{26}, R_{25}, and R_{23} are connected as a voltage divider across the 150-volt supply. Grid voltage for tube V_{15} is obtained from the voltage difference that exists between the junction of resistors R_{25} and R_{23} and the 75-volt reference bus. The cathode potential for tube V_{16} is preset on resistor R_{27}, while the grid potential is determined by the slider arm position on potentiometer R_{30}, which is connected in series with resistors R_{29} and R_{31} across the motor field winding. The grid voltage of tube V_{16}, therefore, varies with the voltage across the field winding. If, for example, the latter voltage increases, the higher grid voltage on tube V_{16} permits more anode current to flow, and the ensuing lower grid voltage on tube V_{15} results in a reduction of direct current in the saturable reactor SR_2 and a lower field current. The speed control dial varies the armature control potentiometer R_{11} and the field control potentiometer R_{27} in such a manner that for the initial portion of the control, that is, for motor speeds up to the base speed, the slider arm on potentiometer R_{11} varies from the bottom to the top, with the arm on resistor R_{27} located at the topmost position. For the speed range above base speed the arm on potentiometer R_{11} remains at the topmost position and the slider arm on resistor R_{27} is moved toward the bottom. The setting on resistor R_{28} determines the maximum motor speed.

In order to limit the armature current to a reasonable value, a current-limiting control is employed, utilizing tubes V_{13} and V_{14}. The grid circuit of tube V_{13} obtains its bias from potentiometer R_{17}; its normal value is beyond cutoff, allowing no anode current to flow through the tube. With an excessive armature current, however, the grid potential becomes less negative, the current through resistor R_7 increases, and corrective measures are instigated as mentioned above. A similar action takes place in connection with tube V_{14}, where the increased current through resistor R_{23} causes the bias on tube V_{15} to change, producing

an increase in the direct current through the saturable reactor SR_2 and, in turn, an increase in field current sufficient to limit or regulate the armature current. Tube V_{14} operates before tube V_{13} when the current reaches the limiting value so as to increase the field excitation to its maximum before reducing the armature current. This same action is obtained during starting of the motor regardless of the speed control setting; the field current can be reduced below the normal value only after the armature current falls below the predetermined value. A Thymotrol drive also includes circuit refinements, which are not shown, like anti-hunting and stabilizing circuits, and, of course, incorporates standard devices such as reversing contactors, overload relays, dynamic braking, and fuses.

10–4. Resistance Welding Controls

The welding of two or more metallic parts by the passage of an electric current is an old process; it received an added impetus with the advent of the transformer as the power supply and has been accepted as a favorite method for joining metals in mass production with the application of electronic controls. Formerly only ferrous materials were welded successfully, but since about 1920 the process has been extended to the welding of brass, bronze, copper, aluminum, resistance alloys, and other metals. The basic principle of resistance welding depends on holding the parts to be welded under pressure, after which an applied current generates the requisite heat at the junction of the parts, the heat being proportional to the resistance at the junction, the square of the current, and the welding time. The electrical resistance of the junction depends largely on the material, the area of contact, and the pressure. Since many welds require completion in a fractional part of a second, pressure, current, and time must be accurately controlled in order to obtain a consistent and uniform product.

The four fundamental types of resistance welding, spot welding, projection welding, butt welding, and seam welding, are shown in Fig. 10–16. They differ primarily in the shapes of the welding electrodes, but projection welding differs from the others in that the heat is localized at certain points or projections. Although mechanical or hydraulic means are also commonly employed, the figure indicates the use of air pressure to hold

the work in contact. For spot welding, the machine may be of the rocker-arm type, in which the upper electrode is attached to an arm that operates by pivotal raising or lowering, or it may be of the press type, such as the one illustrated in Fig. 10–17. In either model, a typical welding cycle consists of a group of four intervals occurring in sequence: a squeeze time, during which pressure is applied to the work; a heat time, which lasts for the duration of the weld; a hold time, throughout which the

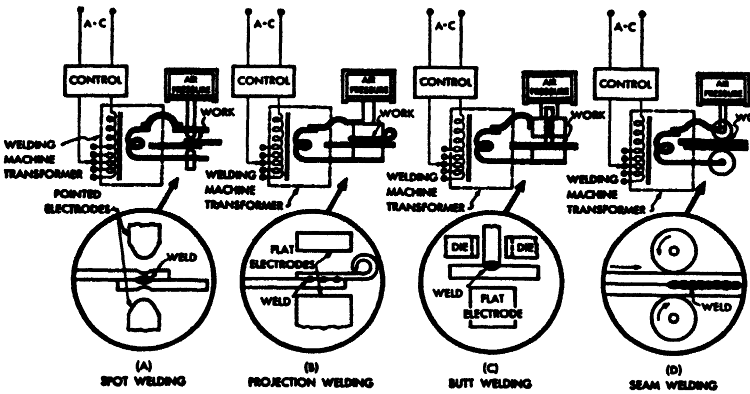


FIG. 10–16. Various types of resistance welding machines, together with cross sections of typical welds. *Courtesy Westinghouse Electric Corporation.*

work is kept in place during cooling; and an off time, wherein the work is removed or advanced to a new welding position. Pulsation welding consists of a modification of a single weld whereby several current pulses that produce several heating and cooling cycles in rapid succession are applied during the welding interval. This method tends to localize the heat and results in better welds for stainless steel and certain other critical materials. Each portion of the welding cycle may vary in time for the duration of 3 to 60 cycles of the a-c supply, depending on the weld; however, each of these intervals must be maintained accurately. To recapitulate, a typical resistance welder consists of the welding machine with its pressure head, welding transformer, and electrodes; an accurately controlled power contactor; a current control to regulate the heat; a timing device to control the intervals sequentially throughout the welding cycle; and a foot switch or other means to initiate the welding operation.

Ignitrons, connected in an inverse-parallel circuit and shown previously in Fig. 6–31 (*b*), offer an ideal solution to the power contactor problem. By equipping the ignitors of both ignitrons

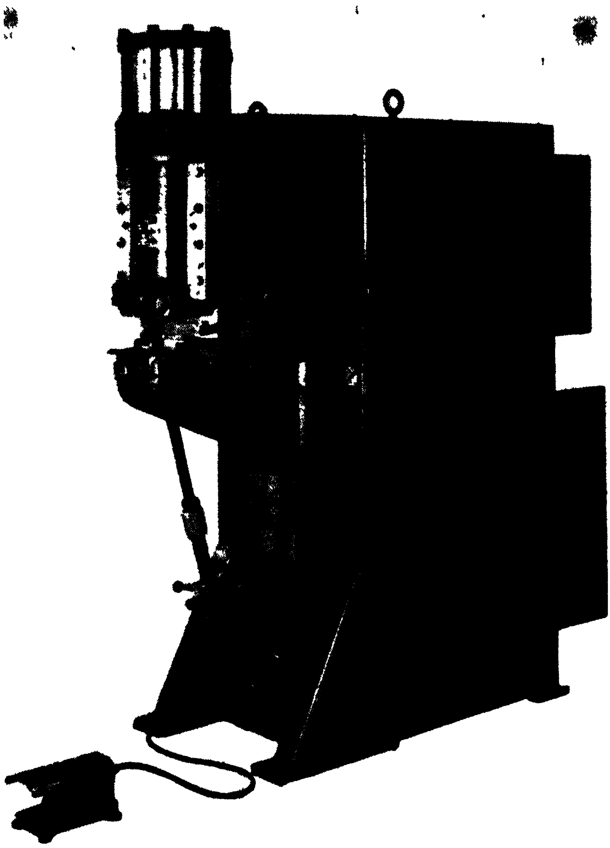


FIG. 10–17. Typical press-type resistance welding machine. Controls are in cabinets at the rear, and the tap-changing switch is located at the lower front. *Courtesy Precision Welder & Machine Company.*

with phase-shift control, the welding current and corresponding heat may be regulated in accordance with the specific welding demands. A sequence timing device for welding consists of a group of adjustable timers arranged so that each timer except the first starts to operate at the conclusion of the preceding interval.

Figure 10–18 shows the various components of a typical resistance welder, with the control circuit in the upper and the power circuit in the lower portion of the diagram. Basically, the control circuit can be divided into six parts: the valve and lock-in circuit, the squeeze-time circuit, the weld-time circuit, the hold-time circuit, the off-time circuit, and the contactor control circuit.

Closing the initiating switch S_1 completes the circuit to relay RY_1 through tubes V_1 and V_2. Contacts S_2 lock in the initiating

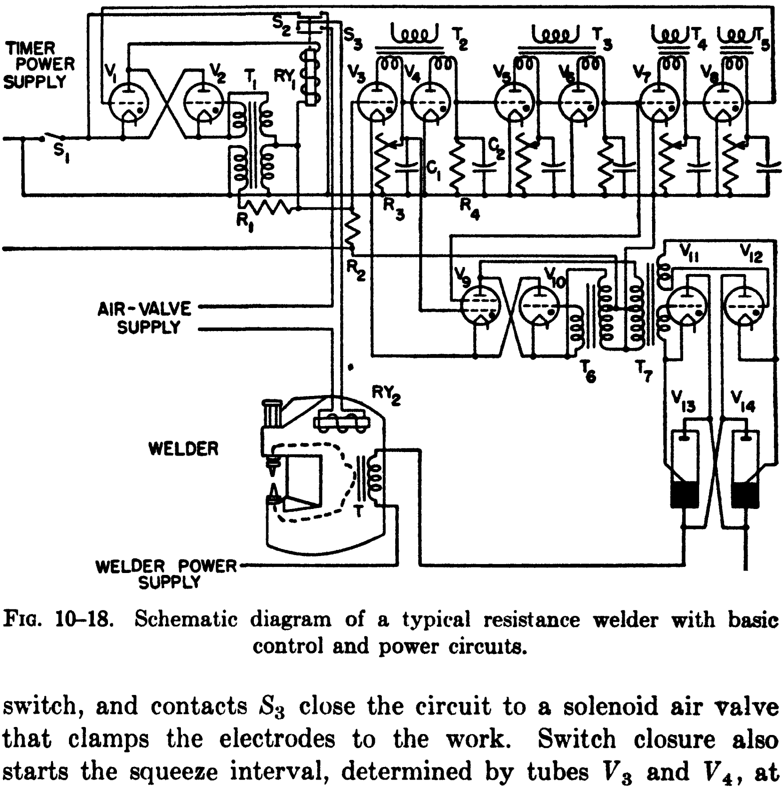


FIG. 10–18. Schematic diagram of a typical resistance welder with basic control and power circuits.

switch, and contacts S_3 close the circuit to a solenoid air valve that clamps the electrodes to the work. Switch closure also starts the squeeze interval, determined by tubes V_3 and V_4, at the conclusion of which the weld interval is initiated, using tubes V_5 and V_6. Simultaneously, the contactor control circuit, using tubes V_9, V_{10}, V_{11}, and V_{12}, operates to produce ignitor currents in ignitrons V_{13} and V_{14}, causing welding current to flow. At the end of the weld time, the contactor control circuit is de-energized, the weld terminates, and the hold-time circuit, using tube V_7, begins to function. When the hold interval has elapsed

tube V_1 is de-energized, the air valve opens to release the electrodes from the work, and, if the initiating switch S_1 is open, the operation is complete, and one weld has been made. If, however, the initiating switch remains closed, the off-time controlled by tube V_8 will expire, after which the welding cycle repeats itself

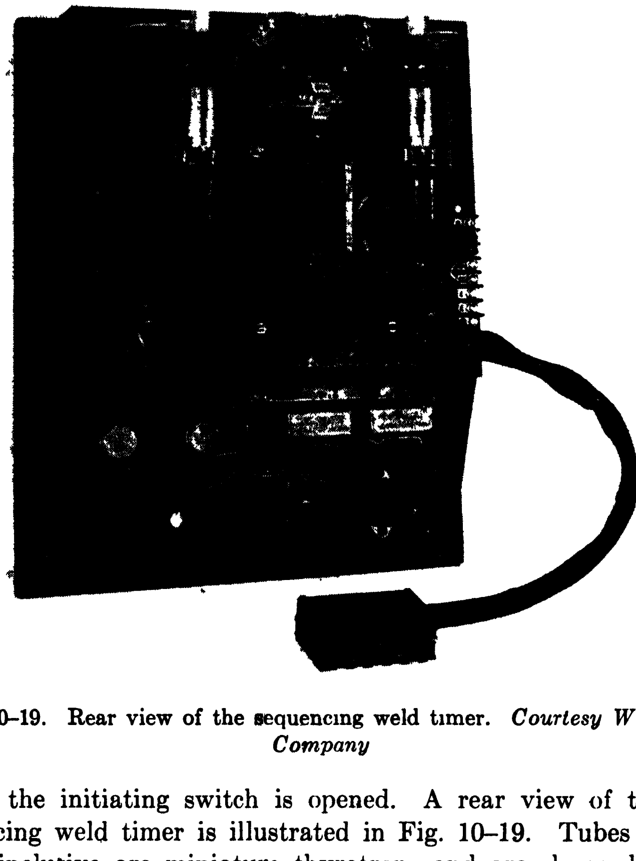


FIG. 10–19. Rear view of the sequencing weld timer. *Courtesy Weltronic Company*

until the initiating switch is opened. A rear view of the sequencing weld timer is illustrated in Fig. 10–19. Tubes V_1 to V_{10} inclusive are miniature thyratrons and are shown located horizontally in the figure; ignitor control thyratrons V_{11} and V_{12} are mounted upright. A front view of the panel on which the control dials are located was previously illustrated in Fig. 6–32.

Only the basic components are shown in the circuit; fuses for ignitron protection, the thermal flow switch for protection against cooling-water failure, the surge suppressor which is connected

across the primary winding of the welding transformer, thyratron grid resistors, and the like are not included. It should be noted, however, that only one relay is used in this circuit and that sequencing is achieved by employing tubes instead of sequencing relays. Grid rectification is utilized to precharge the timing capacitors to insure accurate timing, and proper phasing of the transformer windings is, of course, a fundamental requirement in the circuit.

The previously described timer belongs to the class of nonsynchronous timers that start and stop the flow of welding current at random points on the line-voltage waveform. Many welds use relatively long intervals where a small deviation of heating time is unimportant, and, therefore, such timers are widely used. The second class of timers are the synchronous timers which always open and close the welding current circuit at precisely the same point on the line-voltage waveform. They prevent the occasional momentary abnormal current peaks or power-line surges and insure greater uniformity of heat per weld. In one form of synchronous timer, immediately after a relay closes, an impulse voltage derived from a peaking transformer fires one of the thyratrons that control the ignitor circuit of one of a pair of contactor ignitrons. This action takes place on the first positive voltage alternation following the closure of the relay and, therefore, fixes the time where the first or leading ignitron fires. The thyratron that controls the ignitor circuit of the second or trailing ignitron receives its grid-control voltage from a potential transformer which is connected across the welding transformer. The current pulse through the leading ignitron and the welding transformer causes the trailing tube to fire, and so any weld occurs throughout an integral number of cycles of power current. Timing is obtained as before by the discharge of a precharged capacitor. Synchronous timing finds application in seam welding, where a welding- and an off-period alternate to produce a row of overlapping welds as long as the operator keeps the control switch closed. The result, for example, in container manufacture is an extremely uniform gastight or watertight weld. Heat control for either system is obtained by changing the tap position on the welding transformer or by using an auxiliary phase-shift circuit that determines the firing point of the thyratrons that control the ignitor circuits.

A large amount of heat and a carefully controlled rate of heating are required for the welding of many nonferrous metals, particularly aluminum and its alloys. Ordinary welders can supply this need only by making large peak-current demands on single-phase power lines; stored-energy welders were developed to overcome this limitation. They depend for their operation on accumulating at a low rate energy in the form of either an electromagnetic or an electrostatic field and subsequently delivering the stored energy at a high rate in the form of a weld. Either

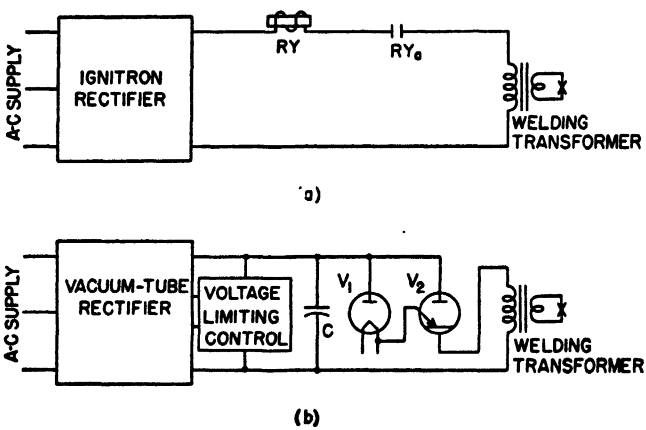


FIG. 10-20. Basic diagrams of energy-storage welding systems. (*a*) Electromagnetic system; (*b*) electrostatic system.

system requires d-c power for its operation; this is obtained through a thyratron rectifier from a three-phase a-c supply line.

In an electromagnetic energy-storage welder, Fig. 10-20(*a*), the electrodes are closed on the work, and after pressure is applied the contactor RY_a in the primary circuit closes. The direct current through the primary winding of the welding transformer increases until the current-limit relay RY operates, causing the contactor to open. As a result of this the energy stored in the electromagnetic field is transferred to the closed secondary winding, where it induces a voltage, and a high-current pulse flows which makes the weld. The magnitude of the welding current is controlled by changing the magnitude of the direct current in the primary winding at the moment of its interruption, that is, by adjusting the current-limit relay.

The electrostatic energy-storage welder, Fig. 10–20(*b*), utilizes a bank of capacitors *C*, which is charged slowly to a predetermined voltage, and a series ignitron contactor V_2, which permits the discharge of the capacitors through the primary winding of the welding transformer when the operator closes the weld-

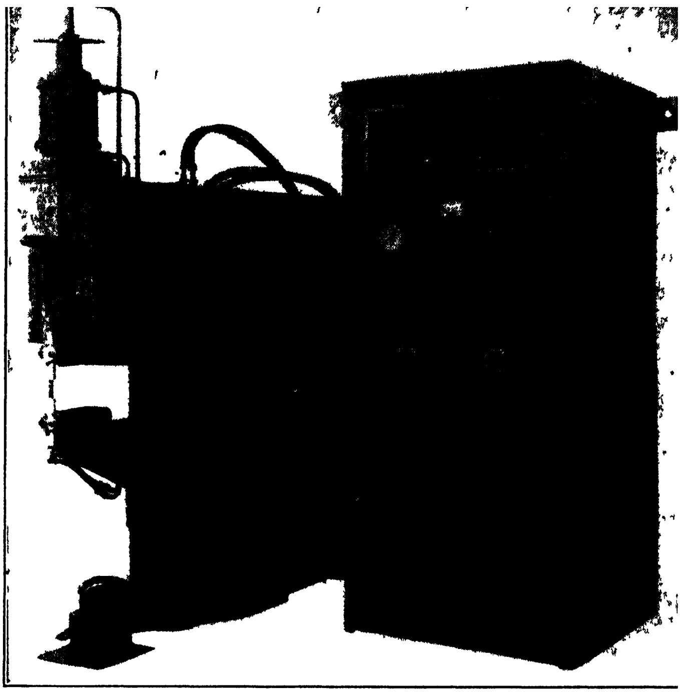


FIG. 10–21 Capacitor-discharge resistance welder, control panel, and welding machine. *Courtesy General Electric Company.*

initiating switch. Capacitors are charged to a voltage from 1000 to 3000 volts, depending on the work. The voltage-limiting control determines the charging rate of the thyratron rectifier; it can also be adjusted to vary the amount of stored energy for different welding jobs. Figure 10–21 illustrates a stored-energy welder of the electrostatic type. The capacitor bank is located in the lower portion of the control cabinet.

Stored-energy welders of the electromagnetic type are usually arranged so that the primary winding of the transformer can be

reversed after each weld to avoid saturation of the transformer core. A similar result is obtained in the electrostatic-type welder by alternately reversing the connections to the capacitor bank. Although electronic control devices for resistance welders may appear to be complex, they utilize ordinary vacuum tubes, thyratrons, and ignitrons in a combination of circuits, each of which generally performs a single function, and which can usually be resolved into one of the basic tube circuits described earlier in the text.

Problems

1. What is the purpose of resistor R_1 in the motor-starter circuit of Fig. 10–2? If this resistor were replaced by one of low resistance, what would be the effect on the motor-starter operation?

2. Redraw the voltage control circuit given in Fig. 10–8 so that it may be used to maintain constant voltage at a distant distribution center instead of at the generator terminals.

3. Rearrange the speed-regulator circuit of Fig. 10–10 for use as a voltage regulator for a compound-wound d-c generator.

4. In the welder control circuit, Fig. 10–18, trace and explain the circuit operation from the moment of closure of switch S_1 to the moment the ignitrons V_{13} and V_{14} begin to fire on the welding cycle.

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11

Electronics in Heating

Flexibility of application, cleanliness, and the absence of an open flame popularized *conduction heating* by electricity. Moreover, the metal part to be heated, termed the work, can also be made the short-circuited secondary winding of a transformer where the induced voltages within the work cause eddy currents to flow that produce *induction heating*. Heating of a specific conductor in this instance is a function of the applied power, frequency, and time. Mercury-arc converters, motor-generator sets, spark-gap converters, and vacuum-tube oscillators, which produce alternating voltages throughout a wide range of frequencies, have been developed as power supplies for this purpose. High-frequency oscillators are also used to supply power for *dielectric heating* where insulating materials, placed in a varying electric field, are heated because of the dielectric losses within the material. This chapter reviews the basic principles of induction and dielectric heating and shows some of their diversified applications.

11–1. Induction Heating Fundamentals

In induction heating the work is placed within a solenoid or other suitable inductor connected to the terminals of an a-c generator, as shown in Fig. 11–1. The alternating magnetic flux induces voltages within the work, causing eddy-current losses, and these with hysteresis losses, in the case of magnetic materials, produce heat. Hysteresis losses occur because of the movement of the molecules in a magnetic material with each reversal of the magnetic field. They are slightly greater or at least com-

parable in magnitude to eddy-current losses at low frequencies and at low temperatures, but disappear at temperatures above the Curie point, which is in the neighborhood of 1350° F for ordinary mild steel; they will be neglected in the discussion that follows.

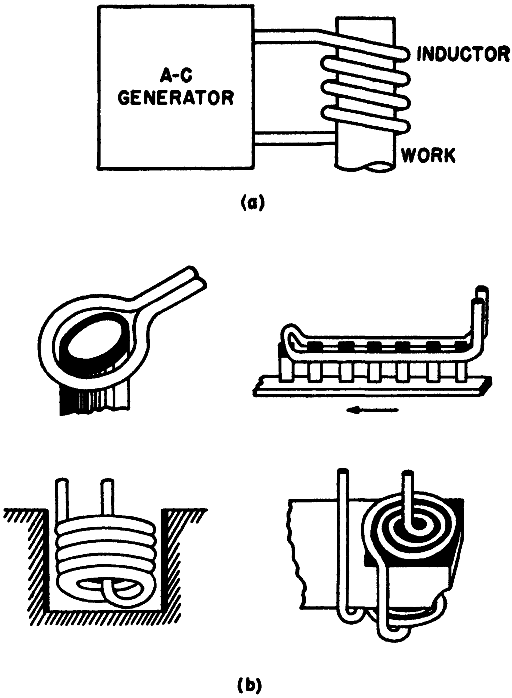


FIG. 11-1. (*a*) Basic principle of induction heating. (*b*) Single-turn, hairpin-type, internal, and series spiral inductors or work coils.

Induction heating is barely noticeable in the laminated steel structure of a well-designed motor or a transformer; if the core were solid, the heat would soon destroy the insulation on the windings.

Heat generated within the work is not distributed uniformly but is largely concentrated at the surface because of skin effect. Eddy-current density is proportional to the effective voltage along its path and inversely proportional to the resistance; the voltage, in turn, is proportional to the magnetic flux within or encompassed by the path. The magnetic flux may be assumed to consist of two parts: the flux produced by the inductor on the

basis that no eddy currents flow in the work, and another flux produced by the eddy currents acting in opposition to the first in accordance with Lenz's law. Since the magnetic flux varies with the magnetization or ampere-turns, the skin effect depends on the ratio of the counter ampere-turns in the work to the ampere-turns delivered by the inductor. This ratio will be nearly zero

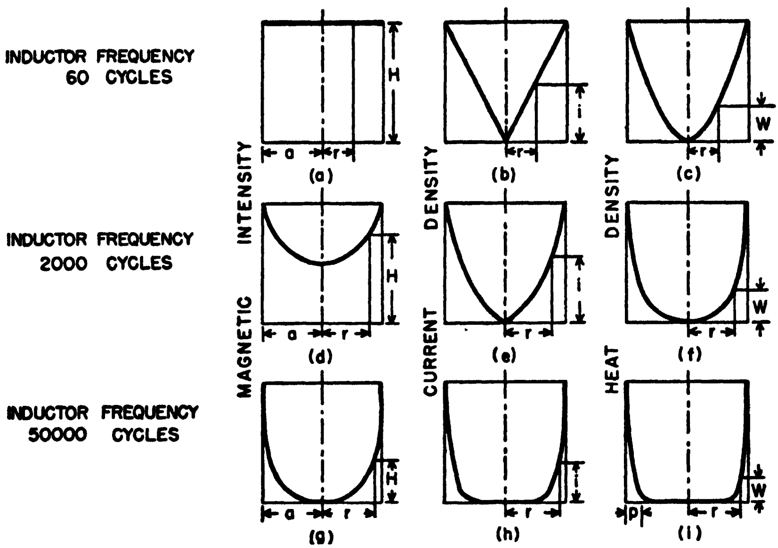


FIG. 11-2. Distribution of magnetic-field intensity, current density, and generated heat density for a round stainless-steel bar at inductor frequencies of 60, 2000, and 50,000 cycles per second. *Courtesy Allis-Chalmers Electrical Review.*

when the counter ampere-turns are negligible, that is, if the resistance of the work is high; if the frequency is low and the resulting induced voltages are small; if the permeability is low; and if the radius of the work is small, because, for similar conditions, work of small dimensions will develop less counter ampere-turns than if it were large.

Magnetic intensity of the field, eddy-current density, and heat generation per unit volume for an inductor frequency of 60 cycles per second, where the work is a round stainless-steel bar, are shown in Fig. 11-2(a), (b), and (c). They are plotted as a function of the radius r and are drawn directly into the elevation view, with the value on the outside of the work assumed as

unity. The magnetic intensity is constant throughout the cross section of the work, with the induced voltages proportional to the square of the radius and the eddy currents proportional to the voltages and inversely proportional to the resistance of the individual paths. Consequently, a linear relationship exists between the eddy-current density and the radius of the work with a zero eddy-current density at the axis and a maximum value at the surface. Since the rate of heat generation is proportional to the square of the eddy-current density, distribution of generated heat is a parabola with the highest density of heat generation at the surface layer of the work and none at the center.

Assuming that the current in the inductor remains constant and that the ratio of counter ampere-turns in the work to the ampere-turns in the inductor approaches unity, the counter ampere-turns are so pronounced that the inductor field is nearly nullified within the work. The opposing action of the eddy currents, as reflected by the reduction of the magnetic field, is most effective along the axis of the cylinder, because the magnetic effects inside a cylindrical current sheet are much greater than those outside it. As shown in Fig. 11–2(*g*), (*h*), and (*i*), the counter magnetomotive force of the eddy currents weaken the original inductor field in increasing measure from the surface to the axis of the cylinder. This results in a greatly reduced eddy-current density and but little heat generation in the interior. This elimination of eddy currents and heat generation from the interior of the work is termed *skin effect*. The inductor frequency in this example is 50 kilocycles per second; for an intermediate value of ampere-turns ratio, that is, for an inductor frequency of 2 kilocycles per second, the results are plotted in Fig. 11–2(*d*), (*e*), and (*f*). For the higher frequencies the distribution of heat generation in the work with respect to the distance from the surface is exponential.

On the basis of the exponential relationship of eddy-current density within the work, calculations may be simplified by defining the *depth of penetration* p of the induced eddy currents as the distance from the surface of the work to the point where the current density has a value of $1/\epsilon$, that is, 37 per cent, of the value at the surface. Since heating is a function of the current density squared, nearly 87 per cent of the total heating takes

place within this shell or layer. Its thickness p in inches is given by the expression

$$p = 3150\sqrt{\frac{\rho}{\mu f}}, \qquad (11\text{–}1)$$

where ρ is the electrical resistivity in ohm-inches, that is, ohm-centimeters divided by 2.54, μ is the magnetic permeability, and f is the frequency in cycles per second. If other factors remain unchanged, the depth of penetration is inversely proportional to the square root of the frequency. It should be noted, however, that the resistivity of the work changes with increasing temperature, and for magnetic materials such as iron, steel, and nickel the permeability also changes.

The magnetizing field produced by the inductor is proportional to the number of ampere-turns, but since the work consists of only a single turn the total induced current, flowing within the work on the basis of unity coupling, is equal to the number of ampere-turns in the inductor. The induced current I_w amperes flows in the surface layer, which has a resistance of R_w ohms and which is given by the equation

$$R_w = \frac{\rho l}{pd}, \qquad (11\text{–}2)$$

where l is the average length of the current path in inches, and d is the length of the inductor in inches, that is, the length of the work exposed to the changing magnetic field. The input power P in watts is represented by I^2R, and, hence, for this case is

$$P = I_w^2 R_w = (NI)^2 R_w = (NI)^2 \frac{\rho l}{pd}, \qquad (11\text{–}3)$$

where N is the number of turns in the inductor, and I is the inductor current in amperes.

The input power density P' in watts per square inch per inch length of the coil comprising the inductor is

$$P' = (NI)^2 \frac{\rho l}{pl'} = (NI)^2 \frac{\rho}{p} \text{ approx.} \qquad (11\text{–}4)$$

where l' is the outer perimeter in inches of the work within the inductor. The simplifying assumption that l, the average length of the current path, is equal to l', the length of the outer perimeter

of the work, yields fairly accurate results with penetrations as great as $\frac{1}{8}$ the diameter of cylindrical work, and the resulting expression for P' provides a simple formula for approximate values of power input. Substituting the value for p, the depth of penetration, from Eq. 11–1,

$$P' = 3.17 \times 10^{-4}(NI)^2\sqrt{\mu f \rho}, \tag{11-5}$$

which shows that the rate of heat input is directly proportional to the square root of the frequency and to the resistivity of the work.

The work can be heated very rapidly by induction heating. For example, in ordinary heating, energy is transferred from furnace walls maintained at a temperature of 2000° F to the work at room temperature at the rate of about 3 Btu per minute per square inch, but in induction heating, energy can be transferred to a piece of steel at the rate of from 100 to 250 Btu per minute per square inch without difficulty. As may be seen from Fig. 11–3, the work within the inductor can be heated almost to the melting point within an extremely short period of time while adjacent portions of the work remain relatively cool. Since an increase in frequency increases heating but decreases the depth of penetration of the eddy currents, it can be shown that for long cylindrical work in melting metal or annealing, where the charge should be uniformly heated in the shortest period of time, the frequency f in cycles per second and the radius a in inches of the work are related by the expression

$$f = 4.82 \times 10^6 \frac{\rho}{\mu a^2}, \tag{11-6}$$

where ρ and μ retain their previously assigned designations.

In general, the nature of the heating operation determines the power supply for induction heating: melting, forging, annealing, and deep surface hardening are best obtained with frequencies from about 1000 cycles to about 10,000 cycles per second, while brazing and soldering, tin flowing on thin sheet, and shallow case-hardening of steel require frequencies which range up to several hundred kilocycles per second. The mercury-arc converter, previously described in Sec. 6–12, is a simple and reliable power supply for frequencies to about 1500 cycles per second. It has a

heating efficiency of approximately 90 per cent, a value higher than can be realized with any other form of converter; its greatest applicability lies in the field of melting metals or through heating metal parts for forging. A mercury-arc converter installation used for melting brass for centrifugal casting machines



FIG. 11-3. Photograph showing concentration of heat in induction heating. *Courtesy Allis-Chalmers Manufacturing Company.*

in a foundry is shown in Fig. 11-4. This unit is rated at 300 kilowatts output, 1000 cycles per second, and 800 volts; it is supplied from a 2300-volt 3-phase 60-cycle power line. Cable connections run from the six anodes of the tank to bushings of the single-phase output transformer, from which cables carry the high-frequency current to the work.

Alternating voltages with frequencies to about 10,000 cycles per second can readily be generated by means of motor-generator sets; in fact, these have been used for many years in induction

heating for alloy melting, heating for forging, and for hardening where thick case depths are held necessary. The set usually consists of a single-phase 400- or 800-volt inductor-type high-frequency generator connected to either a synchronous or induc-



FIG. 11–4. Mercury-arc converter installation for melting metals by induction heating. *Courtesy Allis-Chalmers Manufacturing Company.*

tion motor. Common frequencies are 960, 3000, and 9600 cycles per second; generator capacities range between 20 and 1500 kilowatts; and the heating efficiency of a motor-generator set is usually between 65 and 75 per cent. A 960-cycle induction heating installation of this type in a forge shop, where 56 heaters are supplied by eight 1000-kilowatt motor-generator sets each serving seven induction heaters, is illustrated in Fig. 11–5.

Induction heating problems that require alternating current at frequencies above those supplied by rotating machines and below

those efficiently produced by vacuum-tube oscillators are met by utilizing spark-gap converters. Figure 11-6 shows a circuit for a converter of this type. It depends for its operation on the



FIG. 11-5. A modern forge shop utilizing induction heating. *Courtesy Mullins Manufacturing Corporation.*

oscillatory discharge of capacitor C_2 through the inductor or work coil *WC*. Capacitor C_2 is charged by the high-voltage winding of transformer *T*, and, since it is also connected in series with the variable tuning coils L_1 and L_2 across the multiple

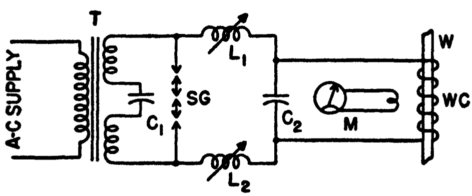


FIG. 11-6. Basic circuit of a radio-frequency generator of the spark-gap converter type.

spark gap *SG*, the combination forms a series-resonant circuit. Both circuits are adjusted by means of the tuning coils to the same frequency, as indicated by a maximum current reading on the loosely coupled ammeter *M*. Capacitor C_1, in series with

the high-voltage winding of the transformer, serves to correct the power factor of the converter. Spark-gap converters produce alternating voltages having frequencies from 30 to 200 kilocycles per second and are made with input ratings from 5 to 32 kilowatts; their heating efficiency is approximately 50 per cent. Hydrogen thyratrons, developed during World War II, can switch a circuit more than 100,000 times per second and offer considerable promise in a converter circuit. Their use provides the shock excitation for the tuned circuits, eliminates the spark

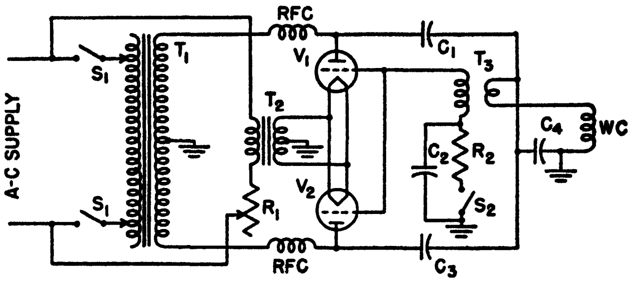


FIG. 11-7. Simplified circuit of a push-pull radio-frequency generator for induction heating.

gap, and results in a high-efficiency device. Although motor-generator sets and spark-gap converters are not electronic devices, they are mentioned here because of their importance in supplying alternating currents economically within certain frequency ranges for a large number of induction heating applications.

Induction heating of small-diameter or thin-section metal parts can only be accomplished by means of frequencies in excess of 100 kilocycles per second. Vacuum-tube oscillators of various sizes and power output from 2 to 200 kilowatts and with a frequency range between 100 kilocycles and 100 megacycles per second are available for this purpose; their efficiency is approximately 50 to 60 per cent. Oscillators are usually operated with a direct voltage on the anodes; however, the design can be simplified, but with the tubes utilized only to a portion of their full capability, by operating them with an alternating voltage on the anodes. A simplified circuit of a push-pull radio-frequency oscillator of the latter type is shown in Fig. 11–7. Only one tube operates at a time, depending on the polarity of the

secondary voltage, and operation alternates between the two tubes. Anode currents flow in opposite directions through the transformer winding, and, therefore, no permanent flux is produced in the transformer core. The output circuit for the high-frequency current consists of the work coil *WC*, which is connected in series with the primary winding of a feedback transformer T_3, the combination being connected in parallel with capacitor C_4 to form a tank circuit. Capacitors C_1 and C_3 effectively connect the tubes to the output circuit but isolate that circuit from the supply source. Output current to the work is controlled by means of changing taps on the primary winding of transformer T_1 and by adjusting the filament temperatures of the tubes by varying rheostat R_1. Operation of the oscillator is controlled by switch S_2, which is connected in series with the biasing resistor R_2, and since a current of only a few hundred milliamperes flows in the grid circuit no special relay is required.

Induction heating equipment is rapidly becoming a necessity in machine shops and manufacturing plants; it is standardized in definite sizes and is often arranged to be portable. The side view of a portable 20-kilowatt unit is illustrated in Fig. 11–8. The oscillator tubes are located in the upper left compartment with the cooling device for forced-air cooling mounted just beneath them. This heating unit is equipped with a mechanism that automatically permits the generator to adapt itself to deliver power over a wide range of load impedances, and also, for any given application, as the load impedance changes during the heating process, the generator maintains a constant output. Automatic adjustment, termed rematching, will be considered in a later section; it is achieved by the relays shown in the upper right portion of the illustration.

11–2. Induction Heating Applications

One of the advantages of induction heating is that the work can be heated in a specific atmosphere, and special or costly alloys can be melted with accurate control of their composition. Low-frequency alternating currents are used for heating the work before forging, for through heating for hardening or annealing, and for heating to produce shrink fits. A typical application of the heating of tubing or pipe used in the fabrication of accumula-

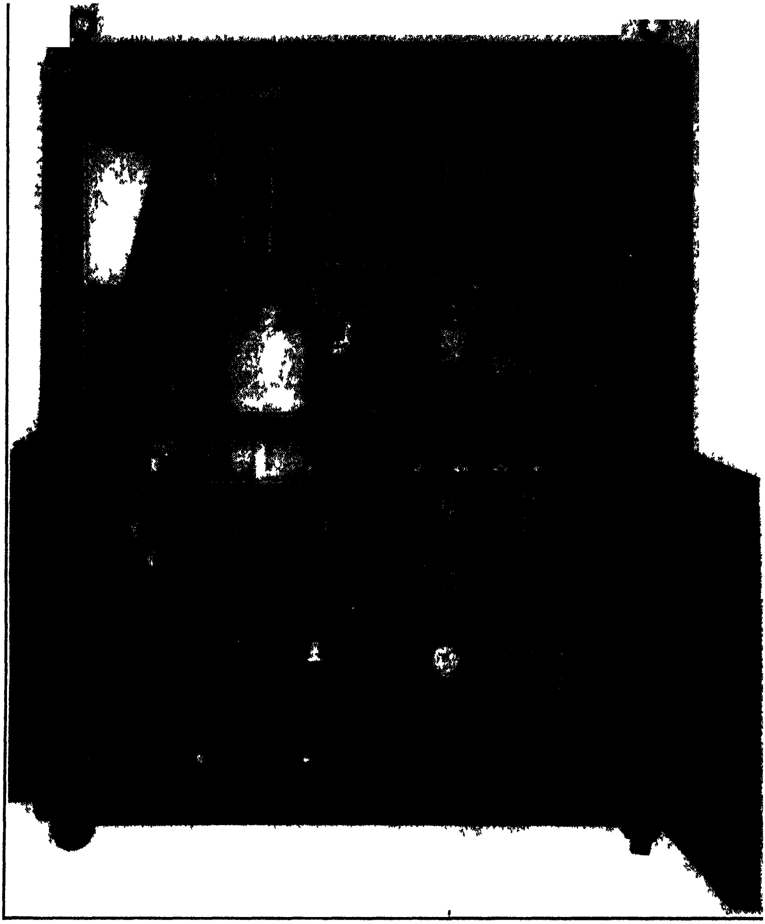


FIG. 11–8 View showing interior of a 20-kilowatt radio-frequency generator designed for induction heating *Courtesy Illinois Tool Works.*

tors and gas tanks is shown in Fig. 11–9. There are three heating positions in the induction heating furnace where three pieces of pipe are heated simultaneously for 2 minutes, after which each in turn is spun to shape in 40 seconds to produce the base of the tank. A similar procedure at another station forms the conically shaped top portion of the gas tank.

Continuous heating by induction of bar stock is widely used for annealing or for heating throughout to a hardening tempera-

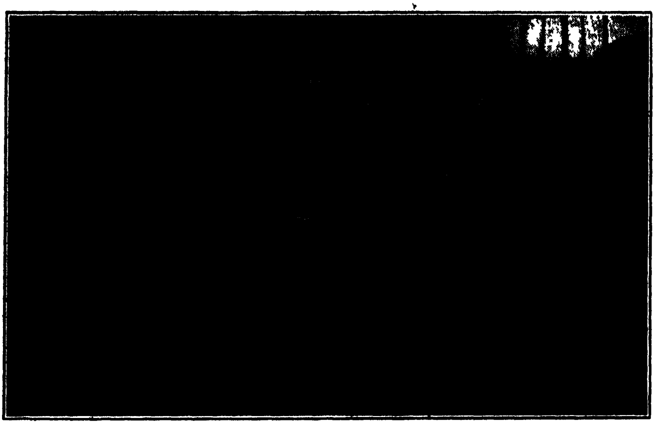


FIG. 11–9. Tubing for gas tanks being heated in an induction heating furnace. *Courtesy United States Steel Corporation.*

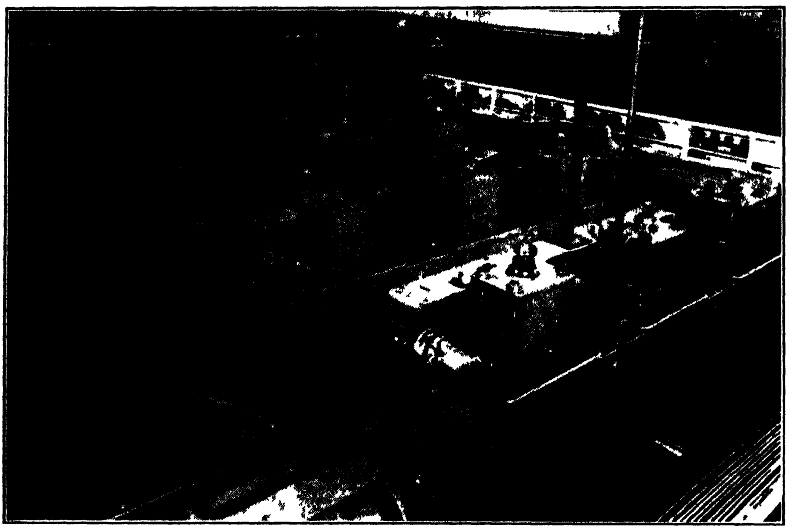


FIG. 11–10. Induction heating installation for the continuous heat treatment of bar stock. *Courtesy Caterpillar Tractor Company.*

ture because of the accuracy and the simplicity of the temperature control coupled with high production speeds. In the installation shown in Fig. 11–10, steel bars progress through special fixtures, being heated to 1600° F in the first work coil, quenched, heated to 1200° F for drawing in the second work coil, quenched, and

finally quenched again to facilitate handling. This method of heat treatment practically eliminates all scale and distortion and provides a uniform sorbitic structure throughout the length and cross section of the bars, unmatched by ordinary batch furnace operation. Bars varying from ½ to 3 inches in diameter are successfully treated on the equipment. In typical production one man can handle 1 ton of 1-inch-diameter stock in 1 hour.

Figure 11–11 illustrates an interesting application of through heating in the field of shrink fitting; it shows the ring gear and hub assembly for the Jeep automobile. The press that performs

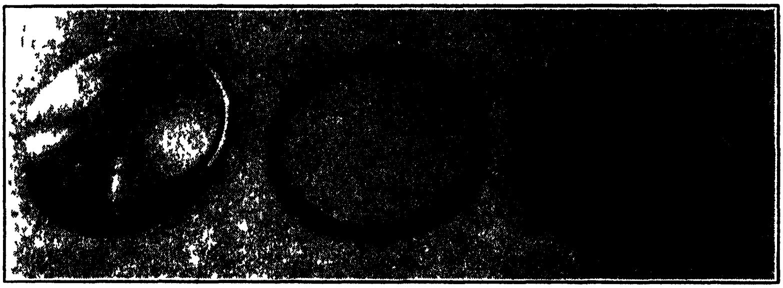


FIG. 11–11. Ring gear and hub assembly of the Jeep automobile assembled by shrink fitting. *Courtesy The Ohio Crankshaft Company.*

the fitting operation is mounted over a 15-kilowatt 9600-cycle-per-second machine, which heats the ring gear to approximately 400° F, causing a 0.025-inch expansion. While heated, the gear is pressed into position, and, on cooling, the gear shrinks firmly to the hub. Designs and operations of this type, which allow the use of two different kinds of materials in the interest of economy, are not new, but shrink fitting by induction heating results in speeding up production schedules by placing the operation in the shop and eliminating a furnace heating and handling operation. Frequently a hardening operation is carried on along with shrink fitting by heating the outer member to the proper hardening temperature and then placing it in position, after which the heated part is cooled rapidly by quenching.

Ordinary furnace heating periods of 5 to 10 minutes are reduced to a matter of seconds with induction heating. Slugs may be heated automatically for upsetting or forging by passing them through a special work coil as shown in Fig. 11–12. Passage of the blanks through the inductor is controlled by a plunger

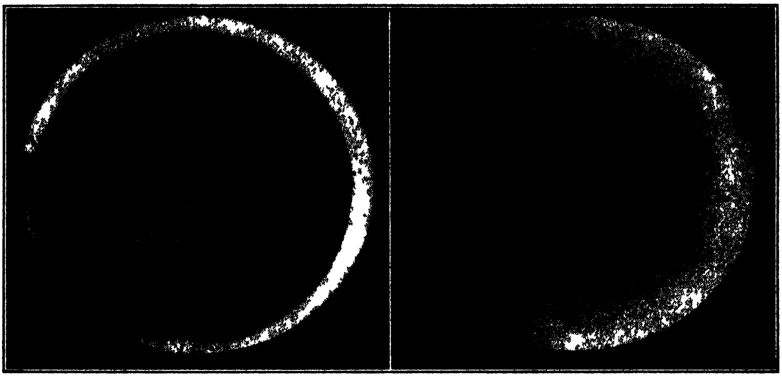
mechanism, and all that the operator does is to keep the chute filled. The specific application shows a 50-kilowatt 9600-cycle-per-second induction heating machine used for heating the bar ends for forging, where 2 inches on the end of bars, 6 inches long by ¾ inch in diameter, are heated to a temperature of 2100° F for forging at the rate of 1 every 4 seconds.



Fig. 11–12. Automatic heating of bar ends for forging. *Courtesy The Ohio Crankshaft Company.*

Saving of time by rapid heating, elimination of a carburizing process by using air-hardening steel, uniformity of hardening which reduces the number of rejects, reduction of oxidation and scaling, and utilization of heat and power only during the productive period add up to induction-heating advantages and savings. And yet, not every instance of surface-hardening of steel by induction heating is economically justified; each specific case must be analyzed individually. Surface layer hardness is seldom the only requirement, for often a ductile or tough core must be maintained, both properties must be controlled accurately, and a specified thickness of the hardened layer must be obtained. The macrostructure of an induction-hardened king-pin, Fig. 11–13(*a*), illustrates how controlled induction heating

gives a thin, hardened surface with a ductile core; the companion photograph, Fig. 11–13(*b*), of a similar piece part heat-treated by conventional methods, shows that the heat penetrated into the core to make the pin brittle and weak. Induction heating for surface hardening is successfully and economically applied to the heat treatment annually of the millions of bearing surfaces of camshafts, crankshafts, gears, sprockets, tappets, and other automobile and airplane engine parts.



(*a*) (*b*)

Fig. 11–13. Microphotographs of transverse sections of kingpins heat-treated by (*a*) controlled induction heating; (*b*) conventional heating methods. *Courtesy Allis-Chalmers Manufacturing Company.*

In order to maintain an accurate cooling rate after heating, care must be exercised in the design of the cooling method; many ingenious fixtures have been developed and are in use. Drills, taps, broaches, and the like are frequently held in a vertical position within the work coil and, after reaching the proper temperature, are released to drop into the quenching medium. Gears are usually hardened within a single-turn inductor, which also carries the quench fluid, as shown in the typical fixture, Fig. 11–14. Power is removed and the quenching liquid is applied as soon as the gear reaches the hardening temperature.

Brazing and soldering can be accomplished effectively by means of induction heating. Carbide tips may be brazed to cutting tools and high-speed tools to mild-steel shanks to conserve costly materials. Often great savings can be made without sacrificing



Fig 11–14 Single-turn inductor used in heat-treating gears *Courtesy Westinghouse Electric Corporation*

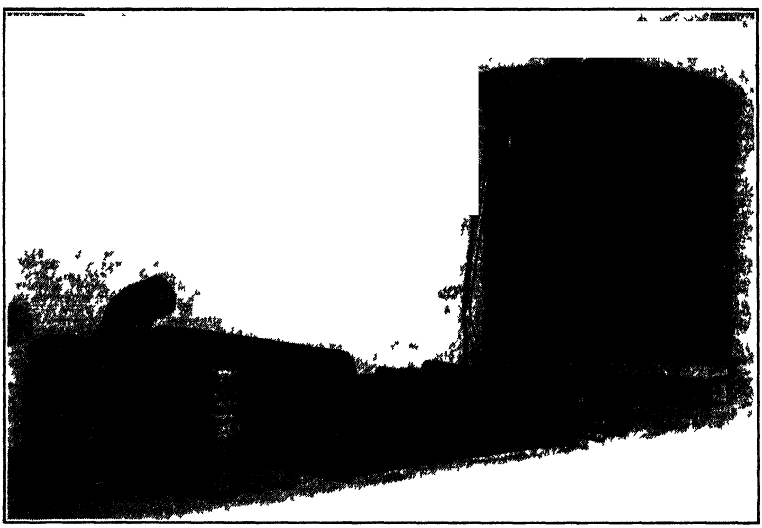


Fig. 11–15 Components and assembly of a tractor radiator soldered by induced heating. *Courtesy The Ohio Crankshaft Company.*

quality by brazing specially heat-treated parts to less costly base materials instead of fabricating the entire structure of the material demanded by the component subject to stress or to wear. Finished assemblies are free from distortion because of the highly localized heat, and the uniformity as well as speed of production make such construction methods popular with production engineers. Figure 11–15 shows a tractor radiator assembly, dismantled and assembled; the component parts consist of the top tank assembly, solder ring, radiator core, solder ring, and bottom tank assembly. A six-station setup, powered by a 20-kilowatt unit, is used to assemble six radiators with the power supplied to each fixture in turn. This induction-heating installation not only increases production substantially but also saves many thousands of dollars annually in solder costs.

As the work becomes smaller in diameter or as the surface layer requires shallower heat treatment, the frequency of the applied voltage must be increased as indicated in Sec. 11–1. For instance, frequencies in excess of 100 kilocycles per second are needed to surface-harden a 0.125-inch-diameter rod, and frequencies in the neighborhood of 400 kilocycles per second are commonly used for the hardening, annealing, brazing, and soldering operations for the multitude of small machine parts employed in domestic appliances and machines. A typical application taken from this field is illustrated in Fig. 11–16 by the 20-kilowatt 450-kilocycle-per-second induction heating machine, employed for annealing the bores of small gears before a broaching operation. The heating time is approximately 2 seconds. The diversified use to which this machine is put is indicated by the assortment of inductors and work coils shown on the board mounted on top of the machine. However, large production schedules warrant automatic production lines, and these are readily installed to perform the desired heating function. As a case in point, one manufacturer used three 20-kilowatt 450-kilocycle-per-second oscillators with special work-handling equipment in 1945 to anneal the ends of 29,000,000 steel pins for a chain-making operation.

Reflowing of electrolytically plated tin on steel offers a striking example of the value of high-frequency induction heating. This method of producing tinplate was evolved because tin can be put on much thinner and more uniformly by electrolytic deposition

than by the hot-dip method. The tin coating after deposition is granular and dull and requires a reflow operation, where the tin is fused to a smooth, bright, and homogeneous layer. Conventional heating in furnaces or in a hot oil bath limits the speed of the strip to a maximum of about 200 feet per minute, while with electrical conduction heating almost insurmountable problems

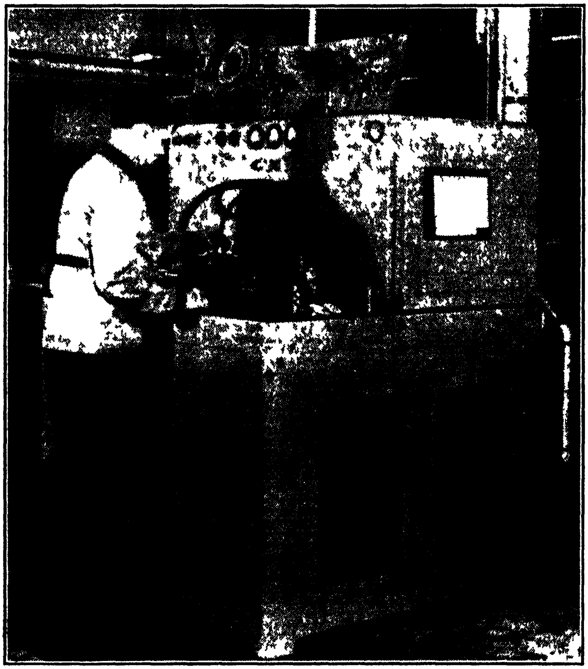


Fig. 11–16 Shop installation of a 20-kilowatt 450-kilocycle induction heating machine *Courtesy The Ohio Crankshaft Company.*

occur in connection with arcing and burning at the contact rolls where the current enters or leaves the strip and in connection with quenching. A view of a tinplating and reflowing line is shown in Fig. 11–17. The tinplate is deposited on the steel strip by an electric current, which is controlled in proportion to the line speed by an electronic regulator. Heating power is supplied by an electron-tube oscillator to a rectangular boxlike work coil shown in the center of the photograph.

A diagrammatic sketch of the tinning line, divided into two

portions for ease in illustration, is shown in Fig. 11–18. This specific line has been designed for operation at 650 feet per minute, with provisions for obtaining speeds up to 1300 feet per minute. The latter speed is about the limit for shearing because

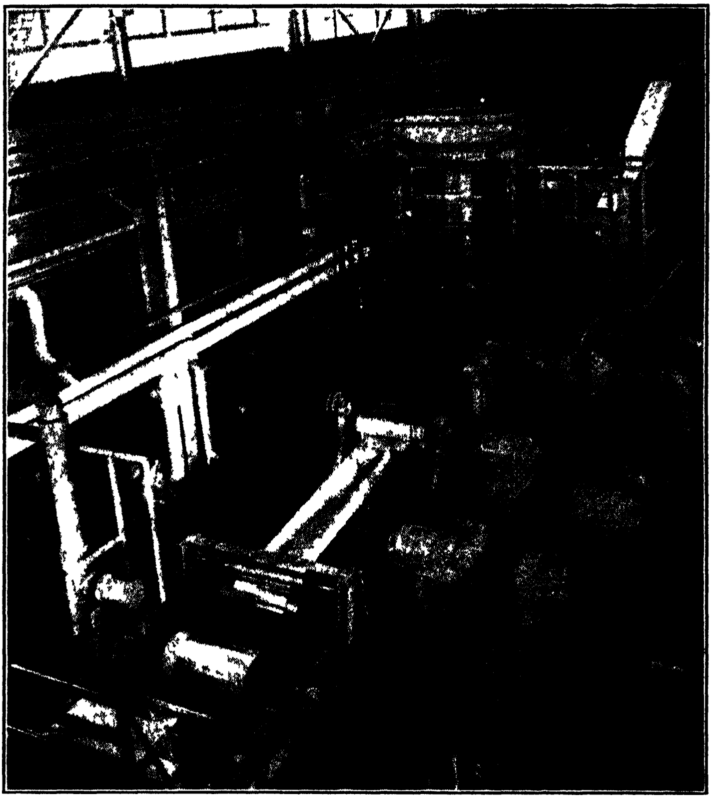


Fig. 11–17. Production line for tinplating and reflowing. *Courtesy Westinghouse Electric Corporation.*

of sheet buckling; consequently, provision has been made for coiling the finished strip into reels between the plating and shearing lines if faster plating and reflowing speeds are deemed desirable. Since tinplate ranges between 0.008 and 0.011 inch in thickness and varies from 18 to 36 inches in width, an induction-heating frequency of approximately 200 kilocycles per second is the most practical. The electrolytic tin coating has a thickness of about 0.000,03 inch, or approximately $\frac{1}{8}$ of that

formerly obtained by the hot-dip process. On the basis of a strip speed of 1000 feet per minute, an oscillator output of about 1200 kilowatts is required. Within 0.7 second after the strip enters the work coil, the strip attains a temperature of 450° F, where the tin melts and flows into a smooth, even surface.

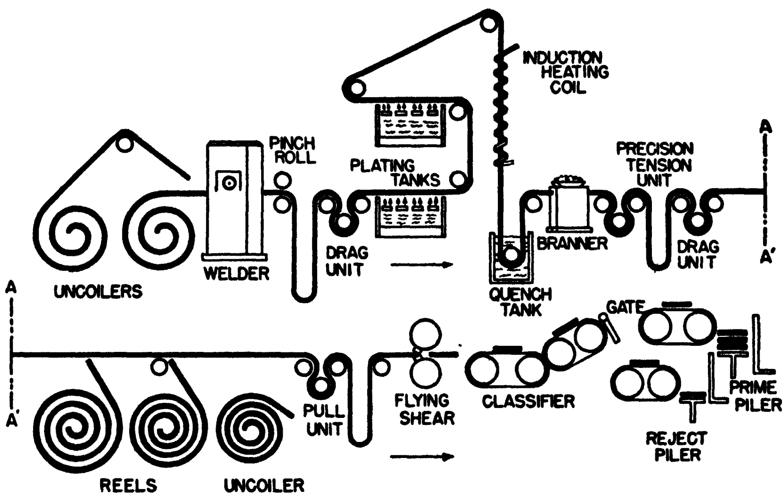


FIG. 11–18. Diagrammatic sketch of the major components of the tinplating and reflowing production line. *Courtesy Westinghouse Electric Corporation.*

The strip is then quenched to harden and preserve this surface, after which it is oiled; the excess oil is removed in the branning machine.

Only the major components of the tinning line are given in the diagram; such controls as loop regulators, where a photoelectric device maintains the length of the loop within specified limits, the photoelectric pinhole detector or the flying micrometer, which detect and shunt defective sheets into the reject piler, and electronic motor-speed regulators, even though essential to the successful operation of the production line, are not shown. The total power requirements for the line at rated load and speed, covering plating, driving, and heating power is about 2700 kilowatts. This process of tinning steel in one line instead of in several separate operations, with the additional advantage of the substantial saving in tin, ranks as one of the major advances in the steel industry.

11-3. Dielectric Heating

Internal generation of heat, due to the periodic displacement of electrons within atoms and molecules of nonconducting materials when placed within an alternating electric field, is termed dielectric heating. The work is placed as a dielectric between two plates to form a capacitor, and an alternating voltage of high frequency is applied to the terminals. Such a capacitor may be represented by a circuit consisting of an ideal or no-loss capacitor C, shunted by a resistance R_P, as shown in Fig. 11-19(a). The vector diagram, Fig. 11-19(b), shows that the

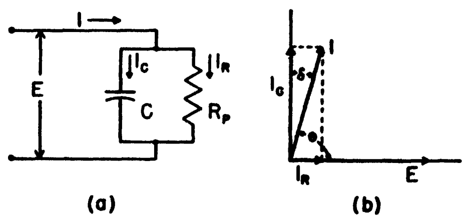


Fig. 11-19. (a) Circuit of a capacitance in parallel with a resistance representing a dielectric heating load. (b) Vector diagram of the circuit.

total current I leads the voltage across the capacitive load by the phase angle θ; the in-phase or resistive component of the current is indicated as I_R, and the out-of-phase or capacitive component as I_C. The power factor of the circuit, or, more specifically, of the material, may be written as

$$\text{Power factor} = \cos\theta \approx \frac{X_C}{R_P}, \tag{11-7}$$

where X_C is the reactance in ohms of the capacitor. For small loss angles δ, that is, for materials of low power factor, we write

$$\cos\theta = \sin\delta \approx \tan\delta. \tag{11-8}$$

The reactance X_C, given in ohms, is calculated from the equation

$$X_C = \frac{1}{2\pi f C}, \tag{11-9}$$

in which capacitance C in microfarads is given by the expression

$$C = 2.25 \times 10^{-7}\,\frac{KA}{d}, \tag{11-10}$$

where K is the dielectric constant, A is the area in square inches of one side of one plate, and d is the distance in inches between the plates.

The power W in watts delivered to the dielectric or work is

$$W = I_R{}^2R_P = EI_R = 2\pi fC'KE^2 \tan \delta, \qquad (11\text{–}11)$$

where C' is the capacitance in farads of the capacitor with an air dielectric. The product $K \tan \delta$ is frequently combined into one constant K', termed the *loss factor* for the material. Making this substitution in Eq. 11–11 and inserting the value for C,

$$W = 1.41 \times 10^{-12} \frac{AfK'E^2}{d}. \qquad (11\text{–}12)$$

By dividing by the volume, or Ad, the power density W' in watts per cubic inch is

$$W' = 1.41 \times 10^{-12} fK' \left(\frac{E}{d}\right)^2, \qquad (11\text{–}13)$$

where E/d is the voltage gradient in volts per inch across the work.

The energy required to heat a given weight of material to the desired temperature is readily determined on the basis that the heat generated is uniformly distributed throughout the material and that heat conduction and radiation losses from the surface are negligible. The heat energy H in Btu is

$$H = wST, \qquad (11\text{–}14)$$

where w is the weight in pounds of the material, S is its specific heat, and T is the temperature rise in degrees Fahrenheit. By converting this expression into watts and dividing by time, the power P in watts required to heat a given weight of material is

$$P = \frac{wST \times 10^3}{56.9t} = \frac{17.5wST}{t}, \qquad (11\text{–}15)$$

in which t is the time in minutes.

Although the heat generated in an insulating material can be calculated more accurately than the heat generated in a conductor by induction heating, there are nevertheless certain factors that affect the final temperature, such as changes in the loss factor, which varies with frequency, moisture, and temperature; heat-radiation losses from the surface of the material; and heat-

conduction losses to the capacitor plates. A serious error is also introduced in the above equations if the work is not in contact with both plates, that is, if an air gap exists between the work and the plates, resulting in a series-capacitor effect.

Dielectric constants for ordinary insulating materials lie between 2 and 10, but certain oxides and some of the newer developed ceramics have dielectric constants that have values up to several hundred or more. Loss factors vary from 0.03 for soft paperboard to about 0.62 for cellulose nitrate. Equation 11–11 shows that effective dielectric heating requires the use of high voltages at high frequencies. Corona losses and arc-over limit the voltage that can be applied to the capacitor plates to about 15 kilovolts, and possible puncture or arcing through the work requires that the voltage gradient be lower than 2000 volts per inch for porous materials and less than 5000 volts per inch for dense materials. Since the heat energy produced within the work is proportional to the frequency, it would appear desirable to use as high a frequency as possible. Limitations, however, usually require that a compromise be made; very high frequencies are difficult to generate with substantial power outputs, and, besides this, they cause standing-wave effects that result in an unequal voltage distribution over the plate area and produce unequal heating. Although frequencies up to 200 megacycles per second are used for special cases, excellent performance is obtained with relatively low radio frequencies. They have been tentatively standardized at 1.7, 3.4, 6.8, 13.7, and 27.4 megacycles per second.

As the load changes, a vacuum-tube oscillator requires constant adjustment if it is to supply maximum power to the load. The dielectric constant and the power factor of a material are definite functions of the temperature, and, as these factors change during dielectric heating, it is advisable to maintain constant power output of the generator automatically. For instance, the power factor of plastic preforms increases during heating, causing the load impedance to decrease correspondingly with the inevitable effect of overloading the generator if the initial adjustment was made to deliver maximum power or rated output. On the other hand, by making the initial adjustment so that maximum power is delivered at the end of the heating cycle, the heating time is prolonged and the over-all heating efficiency of

the generator is lowered. Contrary to that of plastic materials, the dielectric constant of wood decreases to less than one-half its original value as the moisture content changes during drying, and the power factor changes even more so. This means that an originally low-impedance load changes during heating to a high-impedance load, or that the conditions are just opposite to those mentioned previously. By automatic rematching of the load during heating, it is possible to utilize generators of smaller

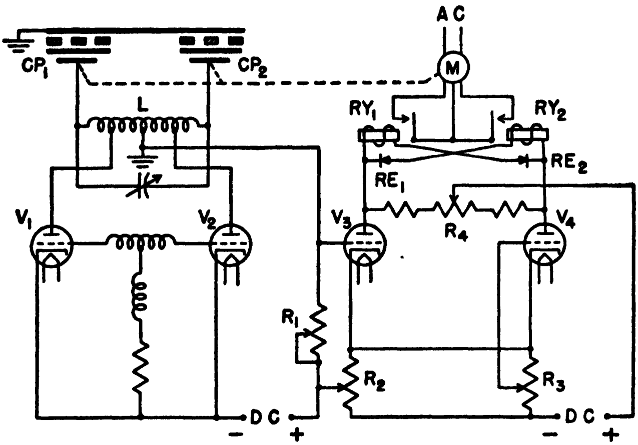


FIG. 11–20. Simplified schematic diagram of a dielectric-heating generator equipped with means for automatic and continuous load rematching.

power efficiently since they are operated at full power throughout the heating cycle. The problem resolves itself into changing oscillator voltages to maintain a constant output irrespective of changes in the load. An alternative solution lies in changing the coupling between the load and the generator, as the load changes, to maintain a constant value of reflected load impedance and, with this, a constant generator output.

Figure 11–20 shows a simplified schematic diagram of a dielectric-heating generator capable of automatic and continuous rematching between load and generator. The generator, consisting of the two tubes V_1 and V_2, is of the self-excited push-pull type, with the center point of the tank inductor L grounded and connected through resistor R_1 to the positive terminal of the anode-power supply. This power supply consists of a conventional vacuum-tube full-wave rectifier, and it as well as the

anode power supply for amplifier tubes V_3 and V_4 are indicated in the lower part of the figure. The load, represented by the material to be heated, is placed between the plates of a capacitor, and these plates in turn are connected to the tank circuit by a pair of additional plates CP_1 and CP_2 that act as a series capacitor. The spacing between the plates of the series capacitor can be changed by means of a reversible motor.

With proper adjustments of feedback and initial coupling for maximum rated anode current of the tubes, maximum power is delivered, and the circuit is matched to the load. As the load impedance changes, the anode current changes correspondingly and this, in turn, changes the voltage drop across the biasing resistor R_1, located in the grid circuit of tube V_3. Tubes V_3 and V_4 are connected as a bridge-type amplifier and arranged with an output circuit, consisting of two relays RY_1 and RY_2, each connected in series with a dry-plate rectifier that permits current to flow through only one of the relays for either unbalanced condition. When the contacts of either relay close, the circuit is completed to a reversible motor M that moves the coupling plates CP_1 and CP_2 to increase or decrease the spacing, depending on the nature of the unbalance.

For the heating of plastic preforms, the generator is initially adjusted to match a relatively high-impedance load, but during the heating cycle, the power factor of the load increases or the load impedance decreases. The increasing anode current changes the grid-bias voltage on tube V_3, resulting in the closure of the contacts on relay RY_1. The motor then operates to adjust the coupling in the direction of a larger coupling reactance by increasing the distance between the coupling plates and the main plates to compensate for the lower load impedance. At the conclusion of the heating cycle, the coupling plates are at their greatest distance from the main plates; that is, they provide minimum coupling between the load and the generator. The next heating cycle begins with the plates in this position, but they automatically move to the position of optimum coupling, where a given fixed and predetermined output of the generator is delivered to the work. A 20-kilowatt dielectric heating unit, used for the preheating of rubber parts before vulcanization, is illustrated in Fig. 11–21. The installation is arranged with the generator unit in the back center; the controls are located on a panel at

the front, and a conveyor system stops automatically for the duration of the heating cycle when the work reaches the correct position between the electrodes. Indicating meters and the work are visible to the operator through a protecting screen. With an entire operating cycle of 1½ minutes, controlled by an adjustable timer, this unit is able to supply approximately 1200 pounds of heated preforms per hour to the vulcanizers.



FIG. 11-21. A 20-kilowatt electronic generator with continuous rematching equipment adapted to the preheating of uncured rubber. *Courtesy Illinois Tool Works.*

The same principle of compensation can also be used for high-temperature heating of ferrous materials in induction heating, where the permeability of the work disappears when the temperature reaches the Curie point. Ordinarily the power absorption drops quite rapidly at that point, but by providing the tank circuit inductance with various taps, rematching for the condition of no permeability in the work can be accomplished through the use of relays that connect the work coil to the appropriate taps when the temperature reaches the Curie point. In other applications continuous rematching for induction heating to a constant temperature of work with a nonuniform cross section can be obtained by using the changing anode current to control a balanced amplifier with a thyratron unit to operate a d-c motor that determines the rate of travel of the work through the work coil.

11-4. Dielectric-heating Applications

Two of the early applications of dielectric heating were rather striking: in one, an elevated temperature or an artificial fever was produced in patients undergoing treatment for certain diseases; in the other, insects, their eggs, and larval forms were exterminated in wheat and other grains. Although a number of hospitals are now equipped with dielectric-heating equipment, and packaged merchandise, such as flour and cereals, can be completely sterilized quickly and economically without changing the characteristics of the product, the application of dielectric heating has had its most spectacular growth in the industrial field of heating plastics, natural and synthetic rubber, textiles, wood and wood products, and in the dehydration of foods and chemicals.

Heating of thermosetting plastic preforms by means of dielectric heating previous to molding has been referred to in the previous section. It may be of interest to analyze the necessity for this in order to appreciate the advantages of this form of heating. There are two methods of molding plastics: transfer molding, where a ram forces the material through a gate into the mold; and compression molding, where the preform is placed directly into the mold to be pressed into the desired shape. In either method the mold is heated by steam or electricity to approximately 350° F. When the mold is closed and pressure is applied, the heat of the mold is gradually transmitted to the material, and, as it approaches the mold temperature, the material becomes comparatively soft and plastic. The applied pressure causes this pliable mass to flow and to fill out the cavity of the mold. With continued application of heat and pressure, a chemical change termed polymerization takes place in which the material hardens or cures into an insoluble and infusible mass. At the completion of the curing process the part is removed from the mold.

It has long been customary to preheat plastic materials in steam-heated ovens to a point at which they begin to soften; by doing this, the mold may be closed more quickly, lower pressures may be used, flow properties of the material within the mold are increased, and the curing time is greatly reduced. Ordinarily, plastic materials are fabricated in powder or granular form, and the first step consists in compressing a carefully weighed amount

into a suitable cylinder-like biscuit or preform. Since the thermal conductivity of most plastic materials is quite low, preforms may be placed only in a low-temperature oven, for if the oven is hot enough to bring the preform to the softening temperature, the outside will harden or polymerize before the inside becomes

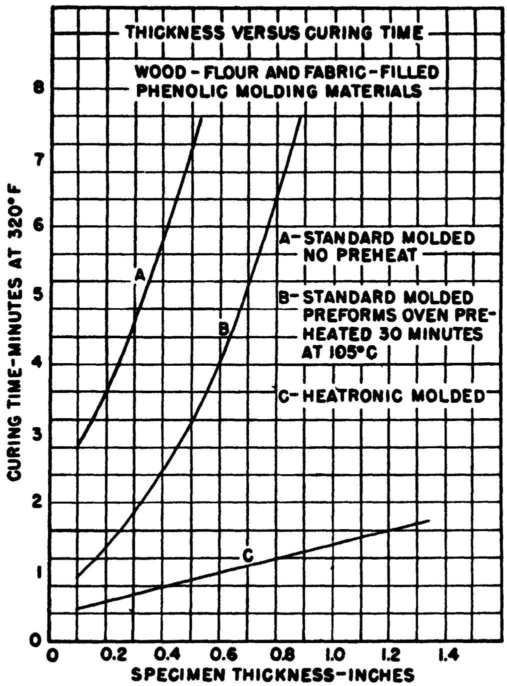


FIG. 11–22. Curves showing curing time advantage of dielectrically heated plastic preforms. *Courtesy Bakelite Corporation.*

soft. Oven preheating of preforms is limited to about 200° F, a temperature well below the softening point. Moreover, the lack of uniformity in the subsequent curing, caused by uneven preheating, is responsible for much of the warpage, loss of strength, and lack of dimensional stability of molded parts.

With dielectric heating, preforms are heated uniformly throughout to a plastic state in a fraction of the time required by ordinary oven heating, as may be seen from the typical heating curves given in Fig. 11–22. The saving in preheating and curing time cycles results in an average increase of 50 per cent or more in

production output, and the uniformity of heating, with the elimination of the surface crust on preforms, reduces scrap by as much as one-half. But complete preheating also permits the material to flow uniformly and materially lessens the danger of displacing inserts or of breaking any pins and projections in the mold. Some molding materials release volatile gases during the molding process; however, if the preforms are dielectrically heated most of these gases escape before the material is placed in the mold, permitting a more simplified mold design. Finally, much lower pressures can be used to compress the material and to close the mold; this advantage is reflected in longer mold life and in reduction of mold repairs. A representative dielectric-heating installation for the heating of preforms in a molding plant is illustrated in Fig. 11–23. For economic production the preheating cycle must be coordinated with press operation; in many cases one heating unit can supply alternately the heated preforms for two presses.

Laminated wood or plywood is ordinarily cured in kilns or between steam-heated plates. Many hours or even days are required for the heat to penetrate to the center of a thick panel, and frequently the glue in the outer portion cures while that in the central portion remains unaffected. Inability to polymerize all the resinous glue has limited the thickness of plywood panels to about an inch. Polymer cements are electrically conductive, and, when plywood assemblies made with such adhesives are placed in a high-frequency electric field, dielectric heating takes place quickly throughout the entire mass, but since the cement has a higher loss factor it heats more rapidly and cures even though the wood laminations remain at a lower temperature. Standard plywood panels are 4 feet wide and vary from 8 to 12 feet in length. Usually a metallic sheet is placed in the center of a stack of plywood to be cured, and the upper and lower plates of the press act as the other capacitor plate; electrically this is equivalent to two smaller stacks in parallel. Stacks of plywood of any thickness up to the capacity of the press may be heated and the adhesive brought up to the curing temperature within a few minutes.

Perpendicular heating in the fabrication of a plywood structure, consisting of a wing bow tip of an aircraft glider, is illustrated in Fig. 11–24. This application of dielectric heating

also shows how this method of curing glued joints speeds up wood-fabrication production and indicates lower operating costs due to lower inventories and reduced storage space. The aircraft part, about 1 inch thick, 13 inches wide, and 16 feet long, is



FIG. 11–23. A 2.5-kilowatt dielectric preheater in a molding plant. *Courtesy Illinois Tool Works.*

composed of eight $\frac{1}{8}$-inch laminations bonded with a urea-formaldehyde thermosetting adhesive, which formerly required a curing time of 4 hours under pressure. A press adapted to high-frequency heating and an output of about 6 kilowatts will reduce the pressing time to $8\frac{1}{2}$ minutes and will reduce the amount of springback in the bow by 75 per cent as compared to a similar



(*a*)



(*b*)

FIG. 11–24. (*a*) Open gluing press for laminated wing bow tip arranged for high-frequency heating. (*b*) Press closed with leads connected to the two electrodes and the safety gate. *Courtesy Steinway & Sons.*

part cured by the conventional cold setting method. Press block and cauls are shaped to the template form, and the capacitor plates consist of a full-size metal sheet on each side of the laminated bow. The part is raised to a temperature of 170° F in the press and remains at this temperature for 1 minute. After the power is removed a cooling period of 10 minutes assures the retention of the bow contour.

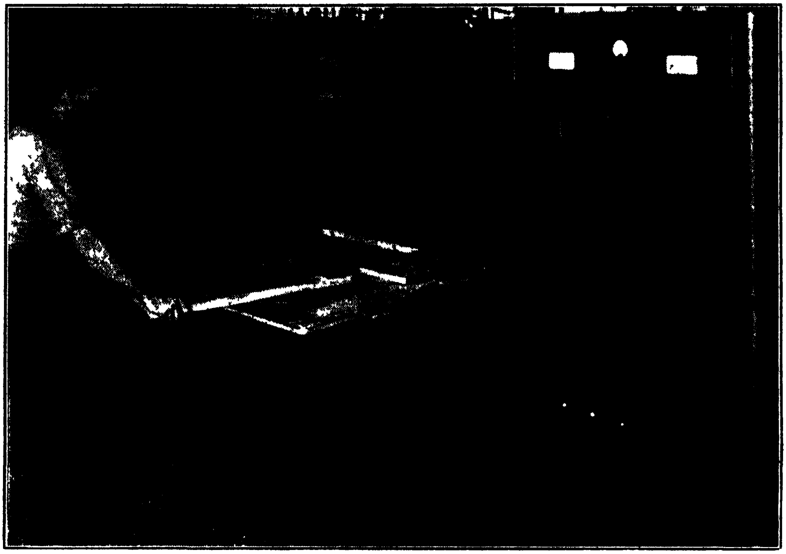


FIG. 11–25. Bonded wood panels leaving the rear of an 8-kilowatt high-frequency press after the adhesive has been cured. *Courtesy Thermex Division, The Girdler Corporation.*

Although perpendicular heating is very effective for adhesives in the manufacture of plywood, considerably higher efficiencies can be obtained by parallel heating where the planes of the glued surfaces are parallel to the electric field. In this method most of the power is absorbed by the adhesive and very little by the wood, requiring much less power and time. However, any excessive adhesive forced out between laminations needs to be spread or removed in order to prevent flashover and charring of the glue along the edge.

An edge-bonding application that illustrates parallel heating is shown in Fig. 11–25, where the press, with a platen 36 inches wide and 42 inches long, will accept wood stock of that width and

length and up to 2 inches in thickness. In a previous operation, glue wheels spread the adhesive only in the center of each edge, leaving a dry strip about ¼ inch wide at top and bottom. When the panel passes through the press, side pressure of approximately 150 pounds per square inch forces the glue to cover the entire area where the bond is desired. This method of gluing does away almost completely with glue squeeze-out and its problems and further increases glue savings. After the press is loaded the operator presses a button, and the necessary operations of closing the press hydraulically, turning on the high-frequency energy for a predetermined heating cycle of 12 to 15 seconds, and then opening the press are carried out automatically in sequence. The panels are then removed, stacked, and delivered to the finishing department where they are planed within 2 hours after gluing and sent on to the assembly line. Besides the tremendous saving in time and greater uniformity of product, a bonding installation of this type saves valuable floor space and releases manpower for other operations in the plant.

Aside from the fabrication of plastic laminates, composed of paper, cotton, asbestos, canvas, and other sheet materials bonded with resins, dielectric heating has contributed to the development of Compregwood, a resin-impregnated wood. This material is made by saturating a stack of wood sheets with resin and then compressing the stack to about one-half its former thickness while the resins are being cured by means of dielectric heating. The resultant product is an extremely dense wood, as strong as steel and capable of being machined and polished. Ordinary heating methods employing steam-heated presses cause the outer plies to become soft first, and when the resin begins to polymerize, pressure must be applied at once even though the interior has not started to heat. The compression is obviously nonuniform, and terrific internal stresses result which can only be partially relieved by long and continued heating. Direct comparisons indicate that practically all these stresses are eliminated by dielectric heating. Although this type of heating is probably not economical for thin material, compregnations above 2 inches in thickness cannot be accomplished successfully without it.

There are many specialized heating applications where dielectric heating offers unique advantages because it saves time or yields a superior product. Consider, for instance, the large

cores used in foundry practice, where prolonged heating to properly dry the interior frequently results in a fragile or brittle outer surface. The vulcanization of large, thick masses of rubber in ordinary steam-heated molds often causes the finished product to have an overcured surface layer and undercured innermost portions. But with dielectric heating drying takes place from the center outward, and rubber is uniformly vulcanized. Proper vulcanization of rubber belting on a batch basis has always been a problem. Continuous rubber belts up to 6 feet in width and 2 inches in thickness can be fabricated by using this newer method of heating. Rayon cords, which make tires safer and stronger, go through two twisting operations after which the 18-pound conical spools of cord pass through a high-frequency field where the twist is set in a few minutes. The spools are carried on a conveyor system, and a single unit sets the twist in about 1000 pounds of cord per hour. Similar applications exist in drying the yarn and setting the twist on nylon and wool.

High-frequency heating is an ideal method of drying out transformer condenser bushings during production. The bushing core consists of a series of equal capacitors with the same volume of paper insulation in each layer. Heating is almost uniform throughout the bushing and reduces the drying time by 8 to 10 hours. Figure 11–26 shows five bushings being dried out on the production line.

One of the many interesting developments of dielectric heating is its use in the dehydration of ceramics, drugs, tobacco, and foods. For instance, penicillin, in order to retain its effectiveness, requires thorough drying before storage or shipment, and the original penicillin solution is so sensitive to heat that it must be kept in a frozen state before and during the drying operation. It has been discovered that in a moderate vacuum the solution can be boiled and evaporated at a temperature of 50° F, and, to prevent foaming of the liquid, vials containing the penicillin concentrate are rotated at 3000 revolutions per minute while in a high-frequency field. This process completes in 30 minutes an operation that previously required 24 hours by the freeze-drying method. Compressed foods can be dehydrated to a water content as low as 1 per cent about 10 times as rapidly as with conventional methods without case-hardening or burning of the food.

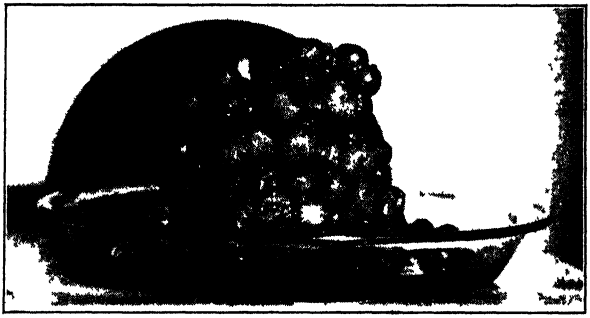
Ordinary large-scale methods of defrosting foods are tedious, wasteful, and costly. Containers of frozen foods are placed in a tank of flowing warm water and remain there until the defrosting is completed. The water cannot be at an excessively high temperature or the food at the edge of the container will be partially cooked during the thawing process. Since the thawing



FIG 11–26 High-tension transformer condenser bushings are dried during production by high-frequency heating *Courtesy Westinghouse Electric Corporation.*

temperature reaches only to the surface of the mass of frozen food, a portion of the food stands in its natural state at room temperature for many hours. It is inevitable that it loses its freshness and often deteriorates to the point where a substantial quantity is ruined. Dielectric heating not only preserves the natural freshness of frozen foods and the fresh-laid quality of frozen eggs, but, by making use of conveyors in large food-processing plants and bakeries, the space and handling labor normally required can be greatly reduced and time schedules can be worked out much more accurately because the materials can be made available in their natural state within a matter of min-

utes. Although Fig. 11–27 shows the high-frequency heating principle applied to a relatively small sample, it has been determined that the thawing period of 30-pound packages of frozen fruits and eggs could be reduced from the 20 hours required by ordinary methods to about 12 minutes by means of dielectric heating.



(a)



(b)

FIG. 11–27. A 3-pound sample of frozen cherries defrosted with dielectric heat (a) Cherries partly melted at the end of 6 seconds; (b) completely defrosted fruit after 11 seconds *Courtesy Federal Telephone and Radio Corporation.*

Furthermore, food continues to heat as long as it is subjected to a high-frequency field, and this principle forms the foundation for the recently developed equipment for rapid cooking of food. A restaurant type 4.5-kilowatt 915-megacycle heating unit is shown in Fig. 11–28. The high-frequency energy, produced by a magnetron, is directed through a wave guide that terminates in

a horn from which it is directed and concentrated into the food. Heating is fairly uniform throughout the food, and heat losses are low because the energy is reflected by all metal objects and is fairly efficiently transmitted by glass; hence, either metal or glass cooking utensils may be used. For the illustrated unit, the food is placed in a disposable paper dish 4 inches wide, 8 inches long, and 1¼ inches deep and is frozen, or it may be at a refrigerated temperature of 40° F. When the food is to be served, the dish is placed in the space provided, the drawer is closed, power is turned on automatically, and the timing cycle begins. After the completion of the timing cycle, the power is automatically turned off, and the food at a temperature of 200° F is ready to be served. Lobsters can be prepared in 2 minutes, a whole fryer chicken in 6 minutes, and steaks and chops in 30 to 40 seconds, depending on whether they are to be rare, medium, or well-done.

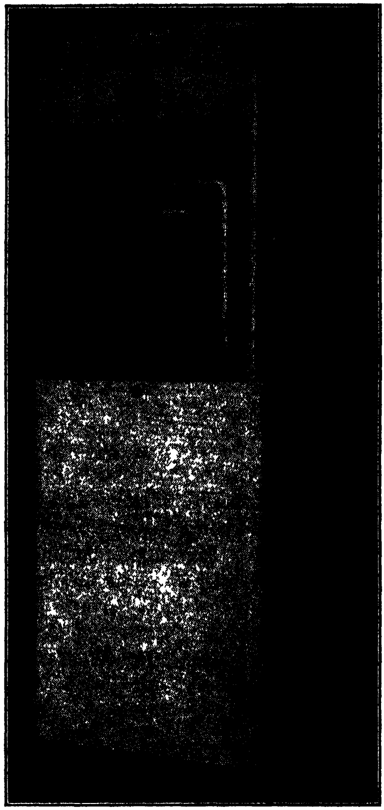


FIG. 11–28. Radarange, a restaurant-type 4.5-kilowatt ultrahigh-frequency heating unit. *Courtesy Raytheon Manufacturing Company.*

At the present time, dielectric and induction heating are the subject of intensive research in many industries; it is only reasonable to expect that these electronic methods, along with other electronic devices, will find new applications during the coming years.

Problems

1. If energy is transferred by induction heating to a steel cylinder 1 inch in diameter and 4 inches long at the rate of 250 Btu per minute per square

inch, calculate the number of kilowatts that must be supplied to an inductor or work coil that has an efficiency of 65 per cent.

2. Calculate the number of Btu per minute per square inch average supplied to heat each bar illustrated in Fig. 11–12, assuming that the room temperature is 70° F, that the heating efficiency of the combination generator and work coil is 70 per cent, that the line of heat demarcation is sharply drawn, and that no heat is lost by convection, radiation, or conduction.

3. It is desired to preheat plastic preforms of urea formaldehyde, each weighing 1 pound and 4 ounces, from 70° to 270° F on a 5-kilowatt 27.4-megacycle dielectric-heating generator, which has an over-all efficiency of 55 per cent. The loss factor, assumed to remain constant during heating of the material at the given frequency, is 0.21, and the specific heat is 0.40. Calculate the heating time for each preform, assuming that no heat is conducted to the capacitor plates or radiated.

4. Calculate the power required to dry 800 pounds of cotton yarn, dry weight, per hour. The ambient temperature is 70° F, the cotton has a specific heat of 0.5, and the yarn has a water content of 40 per cent.

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The literature on electron tubes and their applications is truly voluminous, and it is clearly impossible to list more than a few of the many excellent works that have been written on the subject. Additional information on topics treated in this text may be obtained by consulting the references at the end of each chapter. A few general references are given below.

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Slidefilms with records and 16-millimeter motion-picture films for instructional use have been made covering various phases of electronics. Information regarding them may be obtained from (*a*) Britannica Films, Inc., Chicago, Ill., (*b*) Castle Films Division, United World Films, Inc., New York, N.Y., (*c*) General Electric Company, Schenectady, N.Y., and (*d*) Westinghouse Electric Corporation, East Pittsburgh, Pa.

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